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POTENTIAL OF SPARK IGNITION ENGINE, ELECTRONIC ENGINE AND TRANSMISSION CONTROL

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MARCH 1980

FINAL REPORT

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16. Abstract

This report identifies, evaluates, and documents the characteristics and functions of significant electronic engine and powertrain control systems. Important considerations in the assessment are the powertrain variables controlled, the technology utilized, and the fuel economy gains achieved. A detailed analysis, by engine class and control system technology, is made in order to quantify specific advantages of various electronic systems and their capability to achieve increased engine efficiency and vehicle fuel economy. An attempt is made to identify the minimum technology required to move from the 1978 emission standards of 1.5 HC/15.0 CO/2.0 NOx to the 1981 emission standard of .41 HC/3.4 CO/1.0 NOx with no fuel economy losses. This 1981 standard and the level of technology required to achieve it represents a baseline from which an analysis of further potential fuel economy gains via electronic control systems is made.

17. Key Words
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PREFACE

This report, DOT-TSC-NHTSA-79-55, is one of four companion reports to DOT-TSC-NHTSA-79-52 "Potential of Spark Ignition Engine, 1979 Summary Source Document."* It was prepared under contract to DOT/TSC by Arthur D. Little, Inc. It provides an assessment of electronic control technology hardware for engine and transmission control in future automobiles and light trucks. It does not address control strategies. The latter are addressed in the companion report on "Potential of Spark Ignition Engine, Engine Design Concepts," DOT-TSC-NHTSA-79-56.

This report is a deliverable under PPA HS-027, "Support for Research and Analysis in Auto Fuel Economy and Related Areas."

*"Potential of Spark Ignition Engine, 1979 Summary Source Document," by T. Trella, R. Zub, and R. Colello, U.S. Department of Transportation, Transportation Systems Center, Report No. DOT-TSC-NHTSA-79-52, March, 1980.

METRIC CONVERSION FACTORS

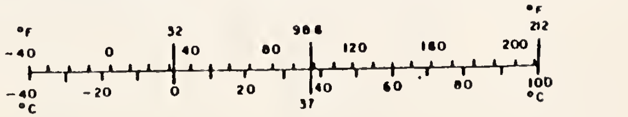
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

1.1 BACKGROUND

Since before 1968, the manufacturers of spark ignition (S.I.) engines have been attempting to meet the increasingly stringent, federally-mandated automotive emission standards. With the coming of the energy crisis in 1974, it also became of national importance to improve transportation efficiency in general and the fuel efficiency of the automobile engine in particular. The oil consumption of the United States transportation sector accounts for approximately 55 percent of the total petroleum used, with the automotive sector accounting for 75 percent of that amount.[1]

The initial attempts by automobile manufacturers to meet the emission constraints caused sharp declines in the fuel economy of a significant portion of the total automotive fleet. The primary reason was that prior to 1975, the techniques utilized to meet the emission standards were those that could be introduced into production with the least modifications to existing hardware. These included excessive retardation of spark timing, and leaner air-fuel (A/F) ratios, primarily for hydrocarbon (HC) and carbon monoxide (CO) control. Also included were lower compression ratios, higher surface-to-volume ratios in the combustion chamber, and relatively high levels of intake/exhaust valve overlap for charge dilution, all of which were primarily for the control of oxides of nitrogen (NOx). The specific problem with these initial attempts at emission control was that the conventional mechanical/pneumatic logic systems used to control these engine variables (spark, charge dilution, A/F ratio, etc.) were incapable of adjusting the amount of spark retard, charge dilution, or fuel to "best" levels under all dynamic engine conditions. More importantly, these systems were incapable of selectively imposing emission controls only during engine conditions that required it and to back off in favor of fuel efficiency under conditions where emission controls were not as critical. (This

is often referred to as optimal weighting). The net result of these non-optimal control strategies was a reduction of the overall efficiency and performance of S.I. engines.

Since 1975, with the introduction of the exhaust gas after-treatment device called the oxidation catalyst, a significant reversal in the trend of decreasing fuel efficiency was accomplished. The oxidation catalyst reduced hydrocarbon and carbon monoxide tailpipe emissions by oxidizing these constitutents in the exhaust stream. This system, along with the development of the exhaust gas recirculation valve (EGR) for charge dilution, permitted engines to be introduced with more advanced timing, higher compression ratios, lower surface-to-volume ratios, and lower levels of intake/exhaust valve overlap. These factors resulted in an increase in engine efficiency that had previously been lost. This change to more efficient engine design was a result of greater flexibility in selectively imposing emission controls in an optimal way via <u>external</u> control devices (catalyst, EGR valves, etc.).

The next most significant emission control technology to be introduced has been that of electronic engine control systems. The continued downward trend in the cost per function provided by integrated electronic circuit technology has made for substantial increases in vehicle use of electronics for many complex control applications. The importance of this technology to emissions and fuel economy has been in its ability to control "key" engine variables (spark, EGR, A/F ratio, etc.) with a greater degree of accuracy, repeatability and speed. The intrinsic speed of response and the flexibility of "computing" non-linear control functions have given the engine control system the capability for following more optimal control trajectories under transient engine conditions. Important also, has been the ability to generate output control signals in response to a multitude of sensory inputs, performing sophisticated time-variant control strategies in an interactive computational sense.

The net effect of this new technology, as it is shown in this study, has been to greatly improve the precision of control of the homogeneous-charge, spark-ignited engines. This improved control enables the fuel efficiency to be maximized for a given mechanical hardware configuration and emission constraint. The study details the automobile manufacturer's current progress with this technology and the potential fuel economy improvements which exist via advance applications of electronic engine controls.

1.2 OBJECTIVE AND SCOPE

It is the objective of this report to identify, evaluate, and document the characteristics and functions of significant electronic engine and powertrain control systems. Important considerations in the assessment are the powertrain variables controlled, the technology utilized, and the fuel economy gains achieved. A detailed analysis, by engine class and control system technology, is made in order to quantify specific advantages of various electronic systems and their capability to achieve increased engine efficiency and vehicle fuel economy. An attempt is made to identify the minimum technology required to move from the 1978 emisssion standards of 1.5 HC/15.0 CO/2.0 NOx to the 1981 emission standard of .41 HC/3.4 CO/1.0 NOx with no fuel economy losses. This 1981 standard and the level of technology required to achieve it represent a baseline from which an analysis of further potential fuel economy gains via electronic control systems is made.

1.3 METHOD OF APPROACH

Before it is possible to fully understand the capabilities of an electronic control system, it is necessary to review what is being controlled and why. In section 2 of this study, an overview is presented of all major engine subsystems with particular emphasis on their functional relationship to emissions and fuel economy. Also included is a discussion of advanced emission control concepts presently under develop-

ment by automobile manufacturers and how the full potential of these concepts may be realized via electronic controls. Section 3 of this study presents the details of presently produced (although in limited test fleet numbers) electronic engine/emission control systems introduced by foreign and domestic manufacturers. A comparison of the fuel economies of these test fleets to the conventionally equipped cars of equivalent engine/vehicle class is given. This demonstrates actual performance of electronic systems to date. Section 4 of this study attempts to define what technologies outlined in Section 2 are required to meet the 1981 emission standards (as stated by the Clean Air Act Amendment of 1977) with no fuel economy losses. From this, a projection of fuel economy improvements into the 1980's is presented. The remaining concepts outlined in Section 2 form the technology base.

2. ENGINE/POWERTRAIN/EMISSION CONTROL CONCEPTS

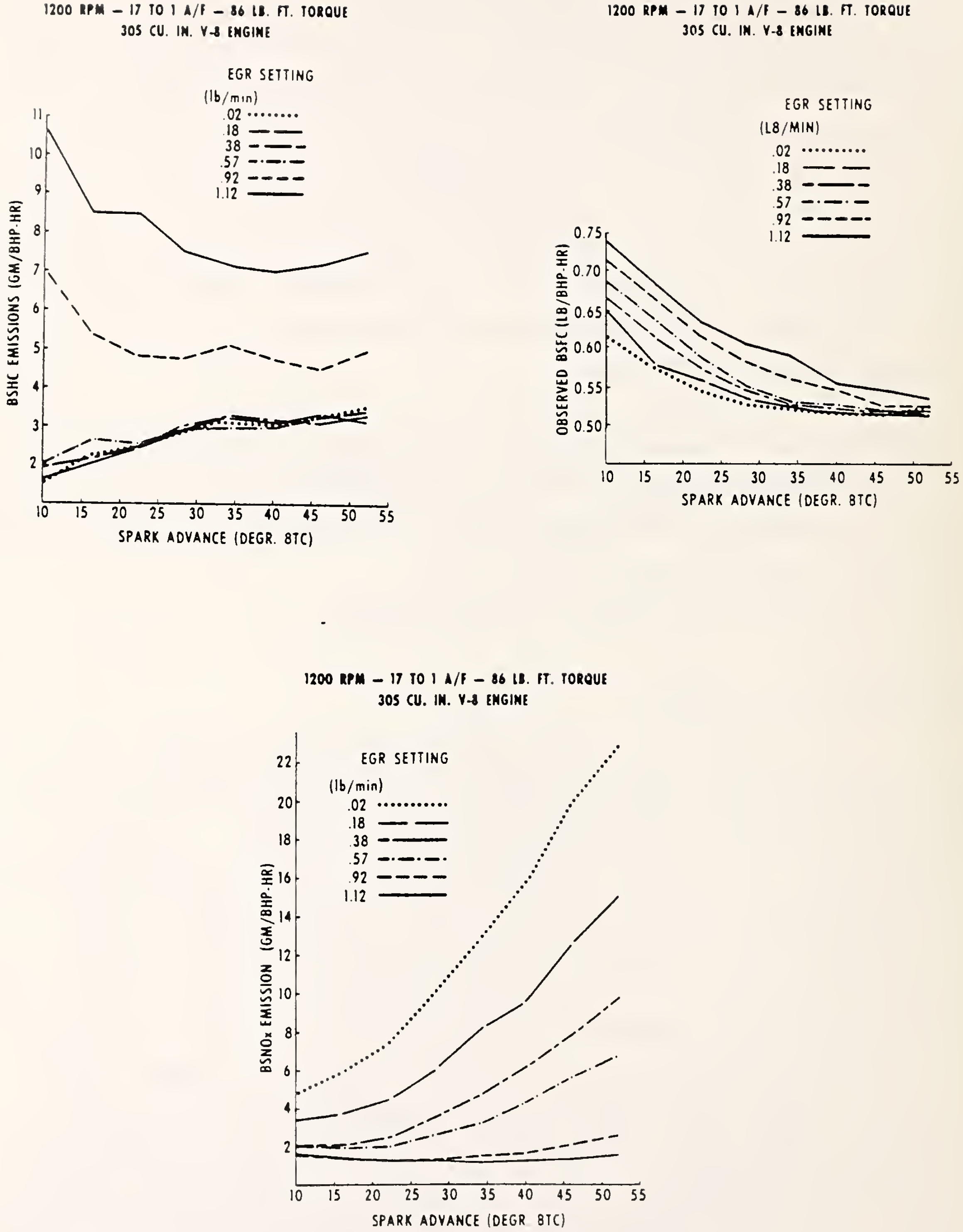
Each engine/powertrain or emission control subsystem discussed in this section has a direct functional relationship to the control of one or more presently regulated exhaust emission species (HC, CO or NOx) with a negative, neutral or positive effect on overall powertrain efficiency. In this section, each control subsystem is reviewed as to its effect on emissions and fuel economy with particular emphasis given to electronic controlability. The following list outlines the subsystems and advance concepts covered:

1. Ignition Systems,
2. EGR Systems,
3. Fuel Delivery Systems (Carburetor, Fuel Injection),
4. Catalyst and Secondary Air Systems,
5. Feedback Control Systems,
6. Transmission Control, and
7. Advance Concepts in Calibration.

2.1 IGNITION SYSTEMS

It is known that both NOx (oxides of nitrogen) and HC (hydrocarbon) exhaust emissions of spark ignited engines are significantly affected by ignition timing. In general, (see Figure 2-1) these emission species decrease substantially with increasing spark timing retard. Spark timing retard is relative to the most efficient operating spark advance which is defined as minimum spark advance for best torque (MBT). Specifically, the chemical mechanization for NOx reduction via spark retard is one of lowering peak cycle flame temperature (to less than 4000°F) during combustion. This method achieves substantial reductions in NOx due to the exponential functional dependence of NOx formation on peak cycle temperature. Ignition timing retard also causes an associated increase in exhaust gas temperature, which in turn, enhances the oxidation of unburned hydrocarbon species in the exhaust stream.

In the early years of emission control, manufacturers relied on simple variations in basic timing, centrifugal advance

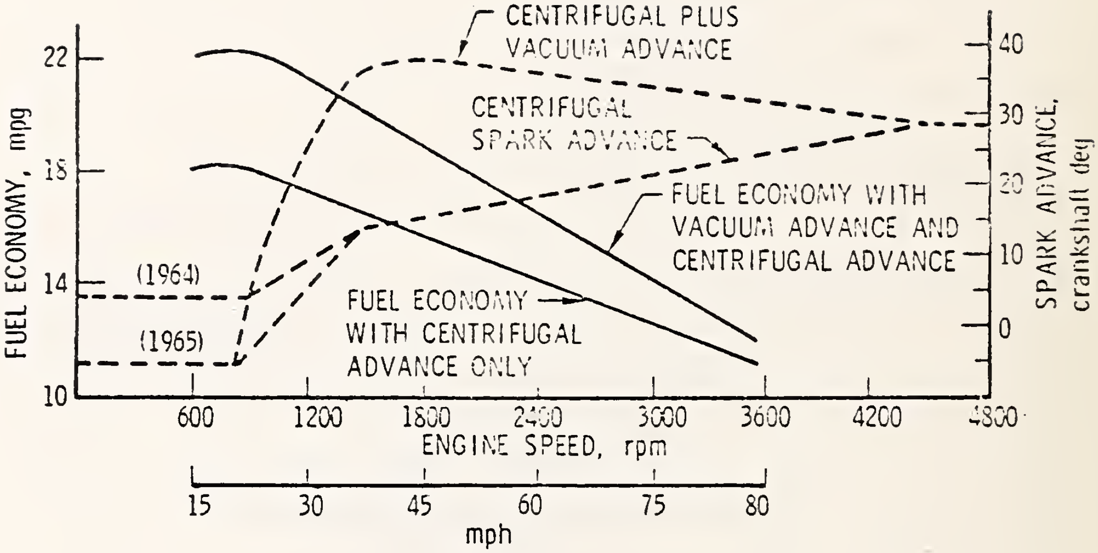


Source: Reference 2.

FIGURE 2-1. ENGINE MAPPING DATA, BSHC, BSFC AND BSNO$_X$ VERSUS SPARK ADVANCE AT FIXED EGR VALUE SETTINGS

and vacuum advance for HC and NOx control. Figure 2-2 indicates the typical relationship of spark timing, fuel economy and engine speed. As can be seen, ignition timing retardation has a highly negative impact on fuel economy. During this time period (1968-1974), the advances in ignition systems were made primarily in the area of improved ignition or spark quality via electronic (solid-state) ignition circuitry. The emphasis was on eliminating the emissions and fuel economy degradation effects (up to 35 percent and 14 percent respectively) of contact triggered systems which suffer from contact point erosion, arcing, metal transfer and wear. Also, due to the leaner air/fuel mixture of the carburetors (for HC and CO control), severe misfires and slow burns could be eliminated only with increases in spark duration, spark energy and spark reliability. These developments led to the introduction of General Motor's High Energy Ignition (HEI) system, Ford's Dura Spark module, and Chrysler's Lean-Burn ignition system. As indicated, these electronic systems improved the quality, instantaneous reliability and long term durability of ignition, but the "when to fire" function or control law was still implemented via vacuum and centrifugal advance mechanisms.

Vacuum advance is implemented by the distributor vacuum unit, which consists of a spring-loaded diaphragm and a vacuum chamber. Vacuum is usually applied through a carburetor ported vacuum system where the vacuum signal is provided by a small port located in the carburetor body slightly above the closed position of the throttle plate. The position of the port, relative to the throttle plate, determines the vacuum advance versus throttle position profile. Centrifugal advance is implemented via a mass-spring system attached to the distributor shaft. The higher the distributor shaft rotation speed (proportional to engine speed), the further the mass moves radially against the spring force, resulting in increased spark advance. In addition, most engines include temperature switches which apply more vacuum (thus more spark advance) at idle under



Source: Reference 1.

FIGURE 2-2. EFFECTS OF CENTRIFUGAL AND VACUUM SPARK ADVANCE ON PERFORMANCE

cold or overtemperature engine conditions. Except for incidences of a spark delay valves in some vacuum lines, this mechanical/pneumatic system defines the production ignition control system on most automobiles through 1977.

In recent years, dynamometer studies[2,3,4] have indicated a much more complicated and non-linear functional dependence for spark advance than the simple control capabilities of centrifugal and vacuum advance systems. It has been shown (see Figure 2-3) that for maximum fuel efficiency within given emission and drivability constraints, optimal spark advance is a highly non-linear function of many variables, some of which are engine speed, derivative of engine speed, intake manifold pressure or engine load, throttle position, derivative of throttle position, intake air temperature, EGR rate, barometric pressure, and A/F ratio (lean or stoichiometric operation). It is obvious that with such complicated interactions among many dynamic variables that a cost effective control method would be to concentrate the "computation" of the control laws into one central electronic module with a multitude of sensory inputs. Chrysler's Lean-Burn system, General Motor's MISAR system and Ford's EEC-I system (discussed in detail in Section 3.) are examples of this control philosophy for spark advance. The electronic and sensory technology required to accomplish this control is defined in Section 3. It is apparent that once a general-purpose central "computer" and sensory system has been justified cost-effectively for improved spark control (as in the case of MISAR and EEC-I), it should be possible to incorporate added functions with the cost increase being primarily memory. As dynamometer studies like Rishavy, Auiler and Dohner,[(2,3,4)] et al., continue to define optional spark advance trajectories and control laws, it will become apparent that on-board centralized electronic computers will be the accepted method of implementation. The following sections (2.2-2.8) outline how additional emission control devices may be integrated into the electronic control system.

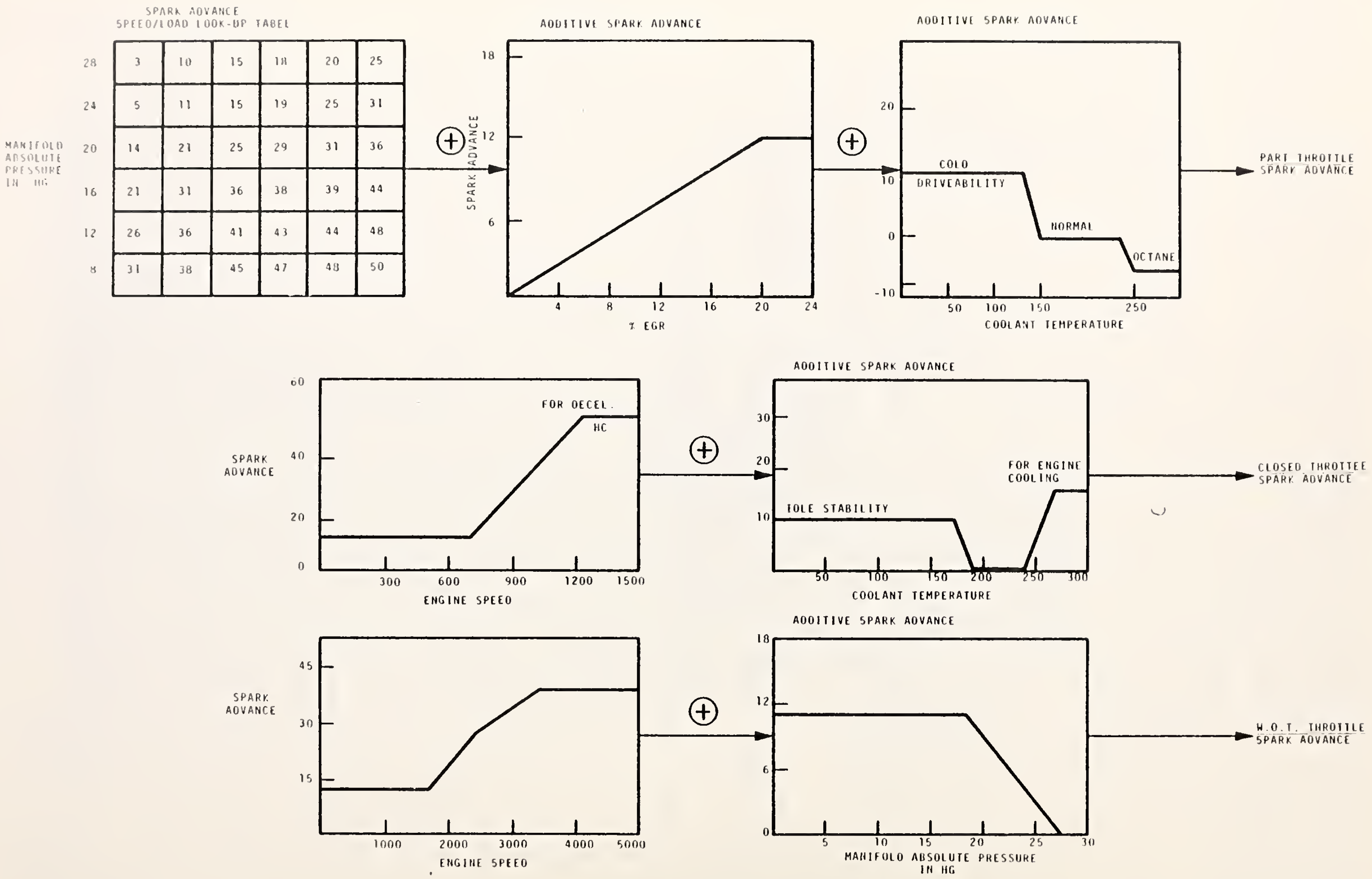
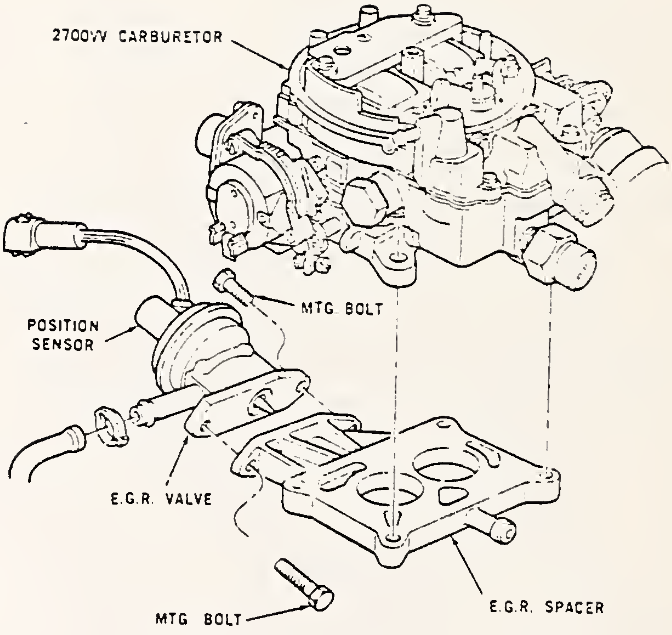


FIGURE 2-3. EXAMPLE OF TYPICAL OPTIMIZED SPARK ADVANCE CALIBRATION

2.2 EXHAUST GAS RECIRCULATION (EGR) SYSTEMS

EGR is a technique by which the charge inducted into the combustion chamber is diluted by the recirculation of gases from the exhaust stream into the intake manifold (see Figure 2-4). There is usually a single point of entry just under the carburetor for homogenous mixing with incoming air and fuel. The dilution of the intake charge with these residual gases reduces the combustion temperature and therefore the NOx formation rates. Before the external EGR valve was introduced, charge dilution was accomplished via modifications of intake/exhaust valve timing. Valve overlap (inlet and exhaust valve opening times overlap) was an effective way of introducing EGR dilution internally by exposing the exhaust system to the low pressure intake system for a longer period of time. Exhaust gases would return to the cylinder through the exhaust valve. Unfortunately, excessive valve overlap degrades overall volumetric (breathing) efficiency, low-speed torque and idle characteristics. These reasons, along with the fact that NOx reduction is only required when the engine is under load, indicate that a system which can modulate charge dilution selectively, better serves the requirements of NOx abatement. The external EGR valve is such a system.

The EGR valve system usually consists of a pintel attached to a spring-loaded diaphragm and a vacuum chamber. The vacuum (or control signal) to the chamber can be modulated several ways. These systems are ported vacuum-modulated, intake vacuum-modulated, venturi vacuum-modulated, exhaust backpressure-modulated, or throttle position-modulated.[1] All of these systems are presently in production and in each case the control signal and therefore EGR flow rate are modulated roughly in proportion to the engine load. In addition, some provision is made to eliminate EGR during idle, closed throttle deceleration, and wide open throttle. Also, most EGR systems incorporate an engine coolant temperature lock-out mechanism which eliminates EGR for improved vehicle driveability during engine warm-up when NOx formation rates are low. Dynamometer



EGR mixes with air and fuel from the carburetor at the entrance to the intake manifold.

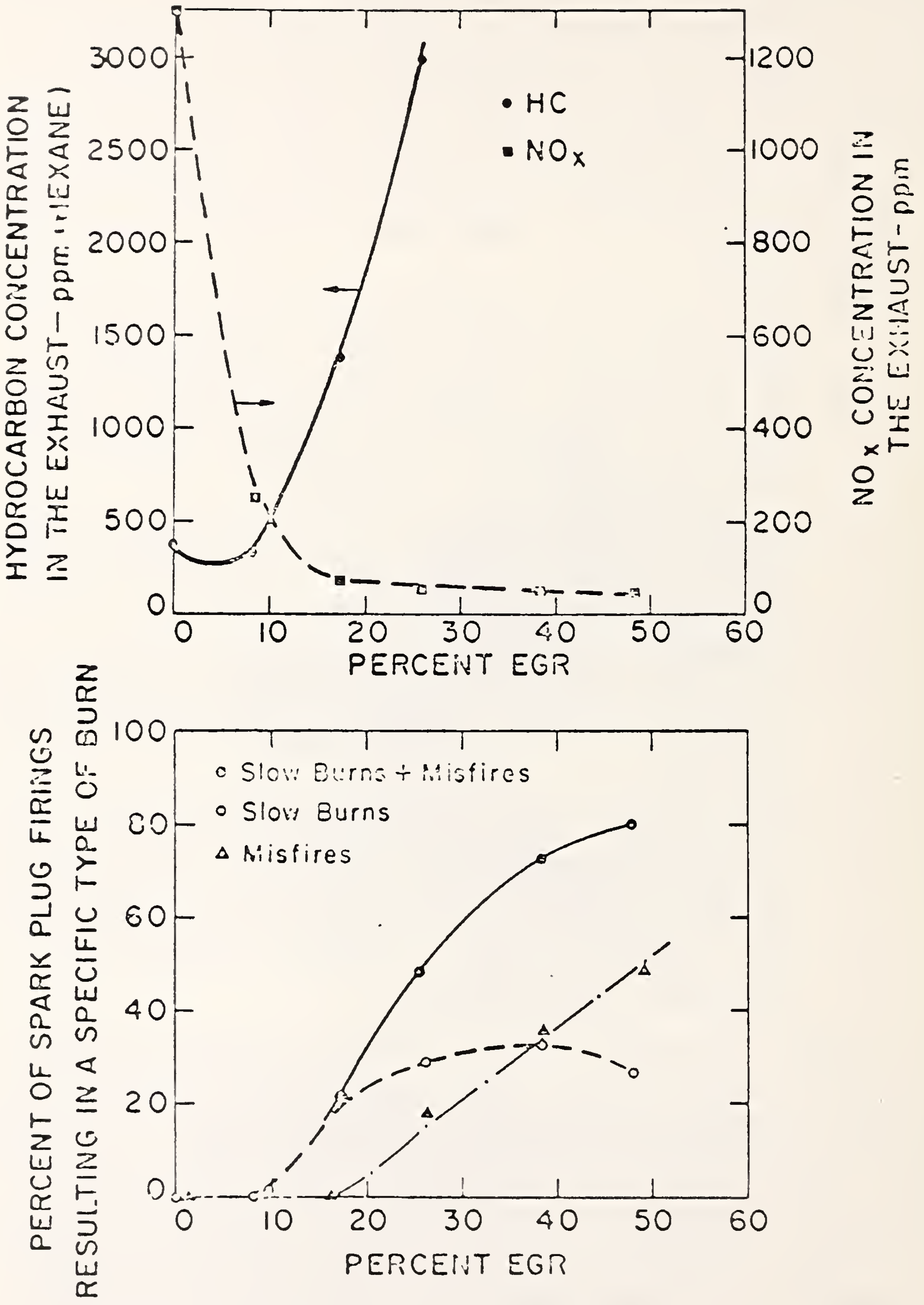
Source: Reference 5.

FIGURE 2-4. EGR VALVE AND POSITION SENSOR ASSEMBLY MOUNTING

studies indicate that the accuracy requirements for the EGR control system are on the order of 3 to 5 percent due to the sensitivity of misfires, slow burns and hydrocarbon formation to inappropriately high EGR levels. The problems associated with today's EGR systems are numerous and relate specifically to the inability of the system to meet this accuracy requirement under dynamic engine conditions. Some of these problems are listed here:

a) Under transient conditions, intake manifold vacuum and load do not hold a linear relationship.
b) EGR flow affects manifold vacuum, thereby causing positive feedback in this typically "open-loop" control system.
c) Dynamic response of EGR valves degrade over time due to wear and clogging with corrosive elements contained in the exhaust gas.
d) EGR valves typically are not sonic flow valves, therefore mass flow through the system at a given control vacuum varies as a function of the delta pressure across the valve.
e) Single point entry under the throttle plate does not deliver homogenous mixtures to the combustion chamber. Maldistribution through the intake manifold is excessive (± 15 percent) and is known to vary with engine load.

In systems terminology, the net result of these issues is that poor control of EGR, both initially and over 50,000 miles, requires emissions compensation from other control variables, namely spark advance and A/F ratio. More spark retard is required to compensate for hydrocarbon formation (see Figure 2-5) either because of inappropriately high EGR levels or to compensate for increasing NOx formation as the dynamic performance of the valve degrades with mileage. Also, the A/F ratio is calibrated richer to eliminate misfires and slow burns associated with poor EGR control and EGR maldistribution. These compensations inevitably lead to losses in fuel economy.



Source: Reference 6.

FIGURE 2-5. THE VARIATION IN THE HYDROCARBON AND NO_X EXHAUST EMISSION LEVELS AND THE AVERAGE STATISTICAL OCCURRENCE OF VARIOUS BURN TYPES AS A FUNCTION OF THE AMOUNT OF EGR, MONITORING CYLINDER 7 OF A 400 CID PRODUCTION ENGINE

Ford Motor Company was the first to introduce electronic control of EGR. This control is part of the EEC-I system introduced with the Lincoln Versailles model (details are discussed in Section 3. of this report) for 1978. This system demonstrates the ability of an electronic control system to eliminate some of the issues mentioned previously. The EGR valve in this system is a sonic flow valve and therefore flow rate is proportional to valve position (independent of downstream pressure). The valve is controlled in a closed-loop manner about a feedback position sensor on the pintel shaft; the feedback gain in the electronic module is a function of error in position which compensates for changes in the dynamic response of the EGR valve actuator with mileage. This also insures that if the valve needs more control signal (in this system the control is via air pressure) to get to a commanded flow rate (position), it receives it, thus compensating for partial clogging of the valve stem. The electronic control system in this case is microprocessor-based and therefore has the ability to decouple the effect of EGR flow on manifold vacuum which eliminates the positive feedback problem often referred to as EGR surge. The same computational algorithm used for decoupling the effect of EGR can be used for computing engine load, although a direct reading of engine torque would be more accurate. The benefit of the more precise and interactive control of EGR is the relaxing of the conservative calibrations of spark advance and A/F ratio resulting in improved fuel economy (∿3 percent) with no loss in emission control.

Besides providing NOx abatement, an additional benefit, is that EGR has been shown[1] to be an effective engine knock suppressant, specifically for A/F ratio operations rich of stoichiometry. Therefore, the engine compression ratio can be increased, resulting in increased fuel efficiency. Unfortunately, the problem of EGR maldistribution due to the characteristics of the intake manifolds and to non-homogenous mixing with air and fuel is left unresolved. Electronics have demonstrated the accuracy and repeatability of control under transient engine conditions but electronics alone cannot compensate for poor

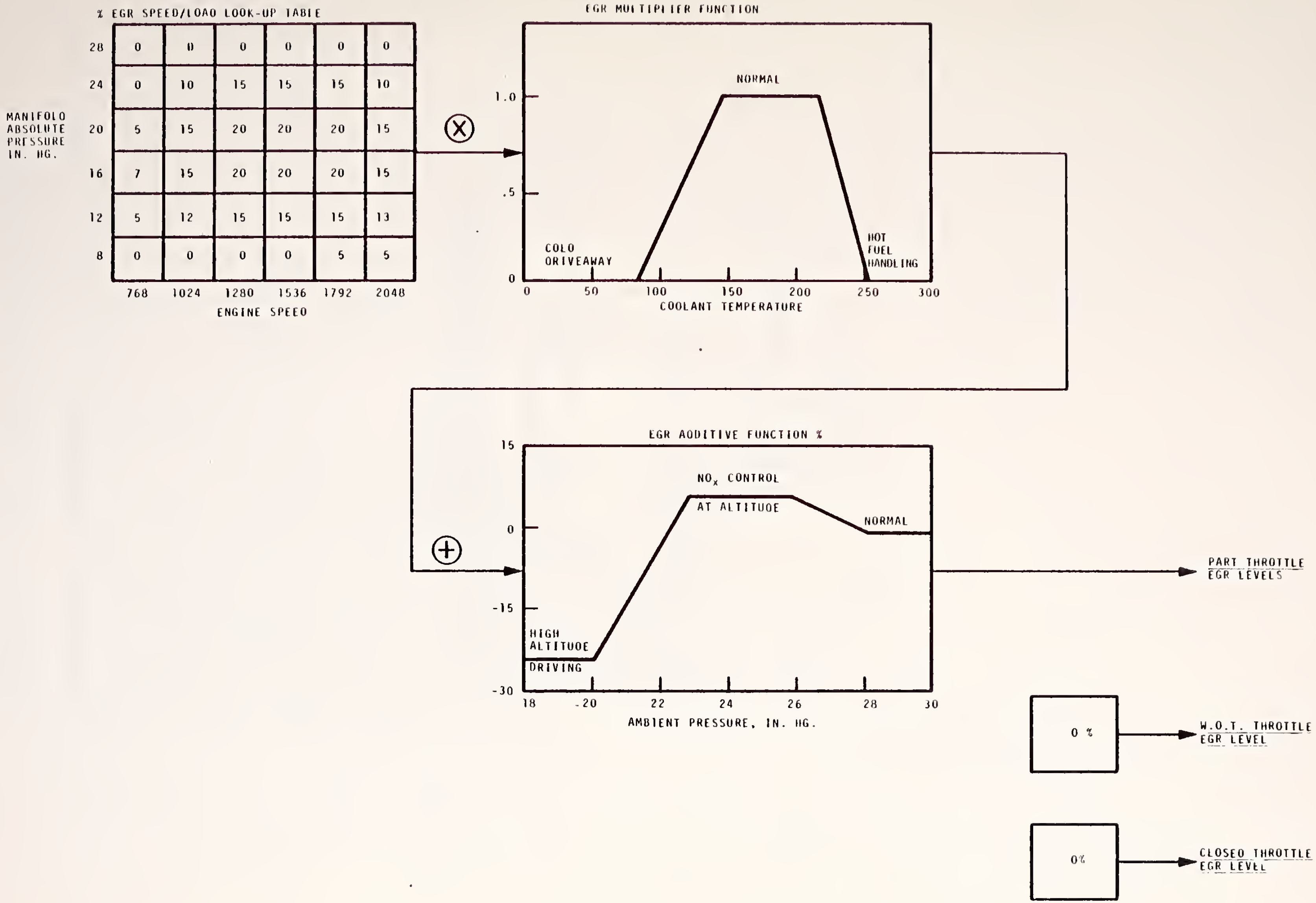
fluid or mechanical delivery systems. Perhaps a computer-controlled variable-valve timing system could selectively (only when required) deliver precise amounts of EGR to each cylinder internally (via variable valve overlap), yielding additional gains in fuel economy which often follows improved accuracy of control.

One last point to note is that the Ford system (ref. section 3.0) indicates that adding control of EGR to the electronic control system for spark is cost effective because the sensory inputs required for spark control are identical to those utilized in the determination of the required EGR flow rate. That is, (see Figure 2-6) the commanded EGR valve position is a function of engine speed, manifold pressure, barometric pressure, inlet air temperature, coolant temperature and the derivative of engine speed. This integrated systems-approach to emission control will become the prominent strategy in the 1980's.

2.3 FUEL DELIVERY SYSTEMS

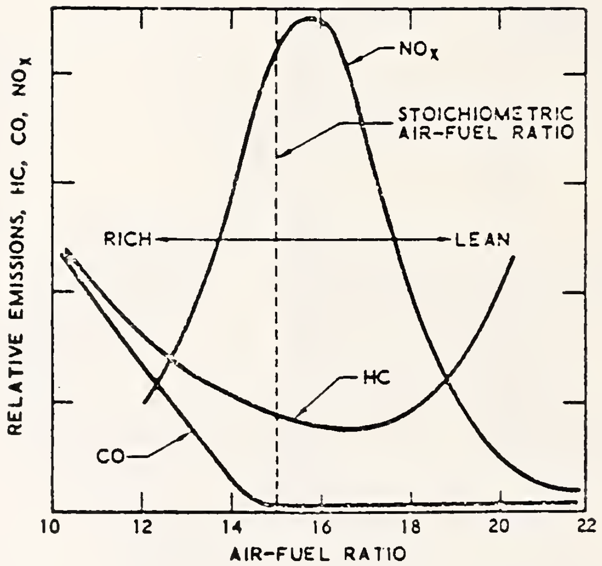
The fuel systems used in automobile engines today are either carburetor-based or of the manifold fuel injection type. In both cases, the fuel systems attempt to deliver the proper amount of fuel to be mixed with incoming air for efficient combustion in the engine cylinders. This precise air/fuel ratio control is required over a wide range of engine speeds, loads, EGR rates, and inlet air densities. Other fuel systems envisioned for future introduction are throttle-body fuel injection and direct-cylinder fuel injection. In this section, the relative merits of each fuel delivery system and potential for electronic controls are discussed. Initially however, there is a need to illustrate the importance of the air/fuel mixture preparation on exhaust emissions. Figure 2-7[7] presents a graph of relative exhaust emissions versus air/fuel ratio in the combustion chamber that is typical for spark ignition engines. As indicated, the air/fuel ratio has a significant impact on NOx, HC and CO formations.

The rate of NOx formation depends strongly on air/fuel ratio and peak flame combustion temperature. NOx levels are



MANIFOLO ABSOLUTE PRESSURE IN. HG.	768	1024	1280	1536	1792	2048
28	0	0	0	0	0	0
24	0	10	15	15	15	10
20	5	15	20	20	20	15
16	7	15	20	20	20	15
12	5	12	15	15	15	13
8	0	0	0	0	5	5

FIGURE 2-6. EXAMPLE OF A TYPICAL OPTIMIZED EGR CALIBRATION



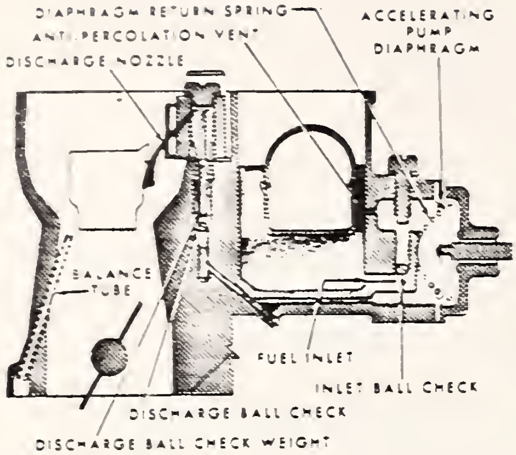
Source: Reference 1.

FIGURE 2-7. EFFECT OF AIR/FUEL RATIO ON EMISSION LEVELS; SPARK-IGNITION ENGINE

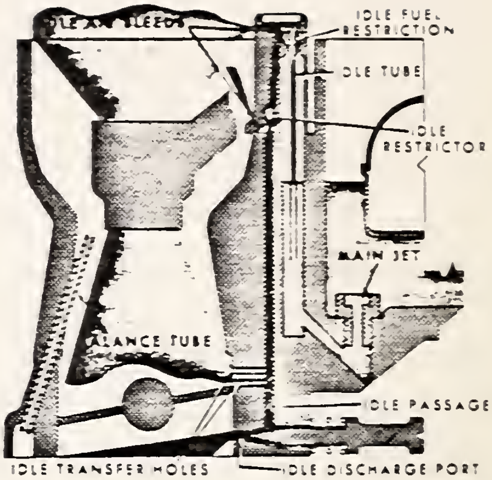
low for fuel rich mixtures (A/F ratio of 12.0 or less) and increase to a maximum for fuel mixtures slightly lean of stoichiometry. The stoichiometric air/fuel ratio (approximately 14.6) is the chemically balanced ratio of oxygen to fuel which completely oxidizes hydrocarbons into water and carbon dioxide during the combustion process. Further leaning of the fuel mixture from this point reduces combustion temperatures as well as NOx formation rates. However, for homogenous charge gasoline engines, air/fuel ratios leaner than 18 to 1 yield drastically reduced combustion temperatures resulting in retardation of HC oxidation reactions. Lean air/fuel ratios also decrease the insensitivity or tolerance to EGR errors and increase the probability of misfires or slow burns resulting in increased HC emissions. On the other hand, overly rich air/fuel ratios result in unburned hydrocarbons and carbon monoxide emissions due to incomplete oxidation and also yield overall reduction in engine fuel efficiency. It is therefore obvious that the important consideration in determining the merits of a given fuel delivery system is the precision of air/fuel ratio control and the degree to which it is maintained.

2.3.1 Carburetor Systems

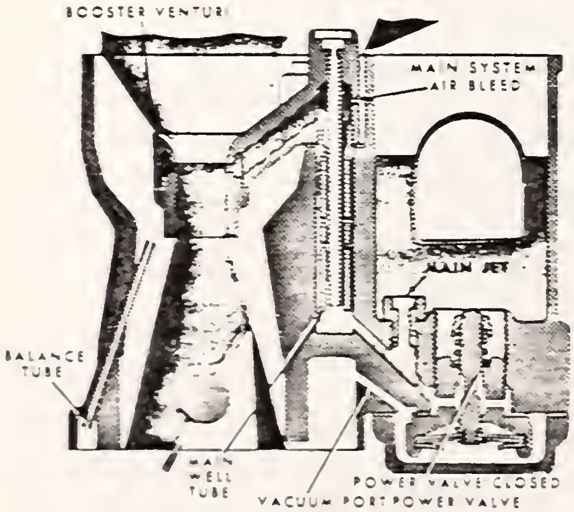
The carburetor is undoubtedly one of the best known engine components from the standpoint of identity, but one of the least understood from the standpoint of its internal operation. A carburetor, in conjunction with its auxiliary subsystems and devices, is an extremely complicated mechanical marvel of springs, levers, bellows, linkages, solenoids and diaphragms. The primary function of a carburetor is to mix the air and fuel as homogeneously as possible and provide a means for regulating engine power (via throttle plates). It must accomplish these tasks over a wide range of engine speeds and vehicle operating modes such as cold-start-warmup, idle, acceleration, deceleration, cruise, high altitude and wide open throttle. Figure 2-8 depicts typical carburetor operations. Some of the parameters



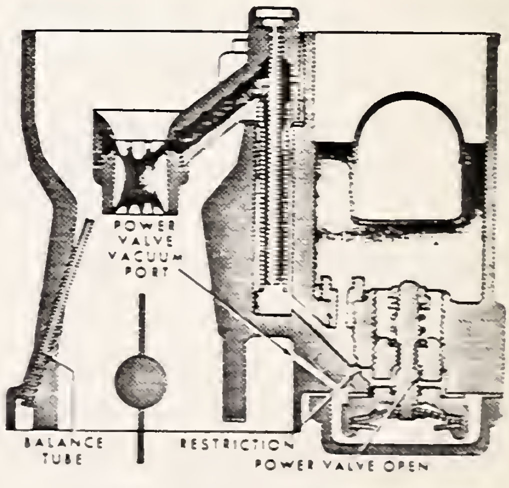
ACCELERATOR PUMP CIRCUIT (AUTOLITE-FORD MODEL 2100 2-V CARBURETOR)



IDLE OR LOW SPEED CIRCUIT (AUTOLITE-FORD MODEL 2100 2-V CARBURETOR)



MAIN FUEL OR PART-THROTTLE CIRCUIT (AUTOLITE-FORD MODEL 2100 2-V CARBURETOR)



POWER CIRCUIT (AUTOLITE-FORD MODEL 2100 2-V CARBURETOR)

FIGURE 2-8. ACCELERATION PUMP, IDLE OR LOW-SPEED, MAIN FUEL OR PART THROTTLE, AND POWER CIRCUITS (AUTOLITE-FORD MODEL 2100 2-V CARBURETOR)

involved in the design and calibration of carburetors are fuel atomozation, A/F distribution, steady state metering accuracy, transient metering accuracy, control start and warm-up A/F control, altitude compensation, air density compensation, and power enrichment. A partial list of the mechanical systems required to accomplish these functions is as follows:

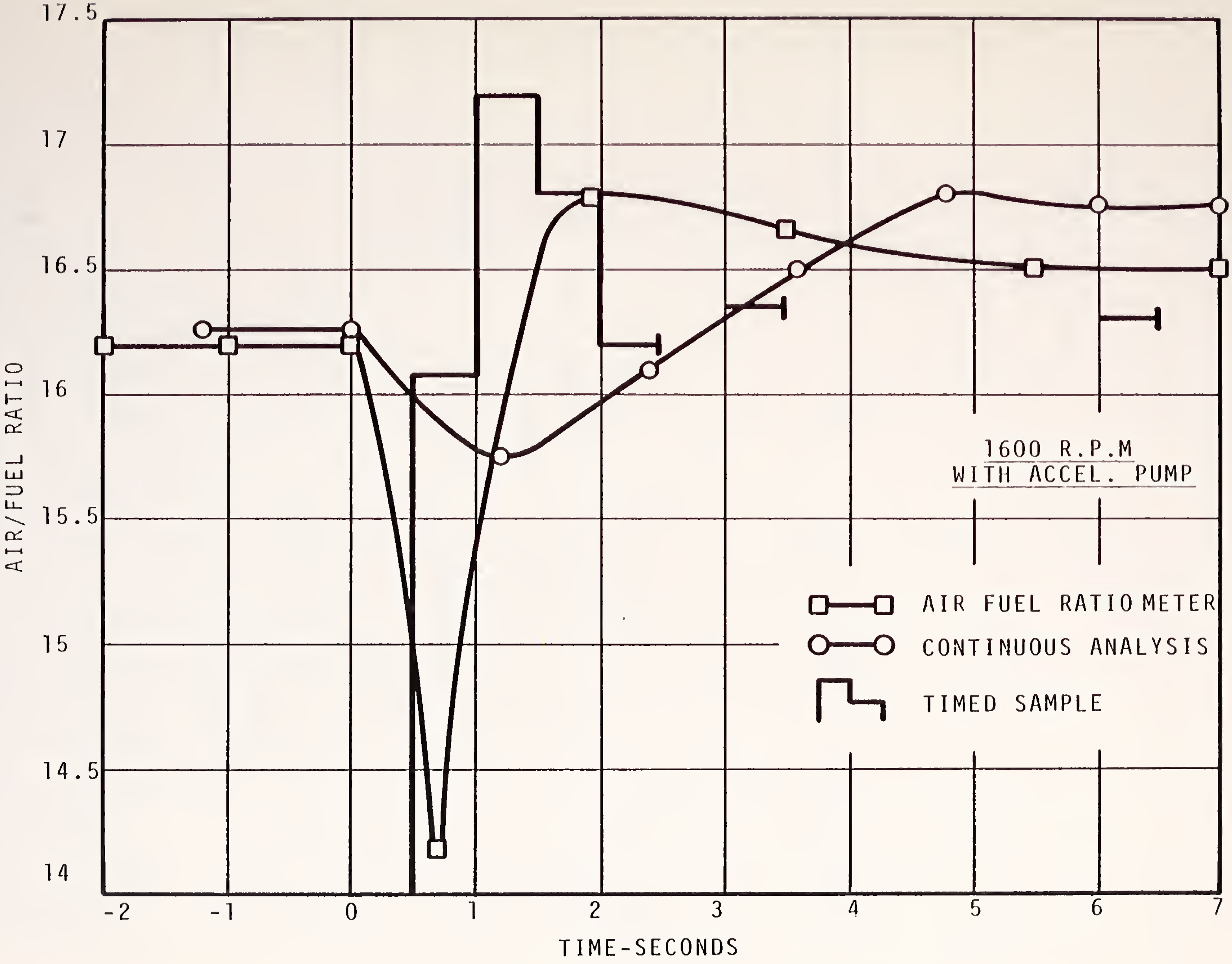
a) Float and fuel bowl venting circuit
b) Automatic choke circuit
c) Idle or low speed fuel circuit
d) Main or part-throttle fuel circuit
e) Power enrichment fuel circuit
f) Accelerator pump fuel circuit
g) Anti-stall dashpot or solenoid throttle positioner
h) Fast idle cams
i) Hot idle compensators
j) High speed air bleeds

The net result of this sophisticated mechanical fuel delivery system is relatively poor A/F ratio control (in production), in the vicinity of ± 10 percent of the desired value and as the system wears with mileage, the performance continues to degrade (± 15 percent of desired value). The problem lies primarily in four areas:

1) manufacturing tolerances and mechanical system wearability
2) carburetor venturi system meters fuel in proportion to volumetric air flow, not mass air flow
3) induction thermodynamics in the intake manifold-plenum system
4) slow dynamic response of the carburetor venturi system

Problem areas 1) and 2) have been addressed through the implementation of electronic close-loop feedback control, the details of which are discussed in Section 2.5. Problem areas 3) and 4) however, are extremely difficult to correct.

The function of the intake manifold or plenum is to take the fuel/air mixture delivered by the carburetor and distribute it uniformly to all cylinders. Unfortunately, a large amount of fuel in a liquid state adheres to the inner surface of the intake manifold, a problem known as manifold wetting. The occurrence is most prominent during cold engine warm-up modes. As the engine is throttled and the manifold vacuum signal varies, the amount of fuel which vaporizes (fuel vapor density) off of the manifold surface also varies, resulting in an extremely oscillatory A/F ratio being delivered to the combustion chambers. In addition to this, the poor dynamic response of carburetors to acceleration transients further complicates matters. The acceleration pump is a device which squirts raw fuel into the manifold in response to rapid throttle movement. Typically fast throttle accelerations, especially from initial positions of nearly closed throttle, will result in a rapid inrush of air. The inability of the carburetor venturi to follow this air signal with the proper amount of fuel causes a lean hole or engine hesitation to occur. The acceleration pump attempts to cover this problem (see Figure 2-9) usually with an A/F ratio disturbance of the order of ±1.5 ratios. The net effect of problem areas 3) and 4) dynamically interacting is the ±10 percent accuracy number stated earlier. The potential for electronic fuel control is not great for carbureted systems. Even the electronic closed-loop feedback control system discussed in Section 2.5 has only the capability of correcting for relatively slow changes in system calibration caused by changes in fuel, temperature, atmospheric pressure and aging of components. Electronic feed-forward fuel metering is more readily applied to fuel injection systems and it is believed that as the NOx and fuel economy standards become more stringent these systems will eventually eliminate carburetor-based fuel delivery systems. The following paragraphs outline the relative merits of electronic fuel metering systems.



Source: Reference 16.

FIGURE 2-9. COMPARISON OF TRANSIENT AFR MEASUREMENT METHODS, FORD 351 CID

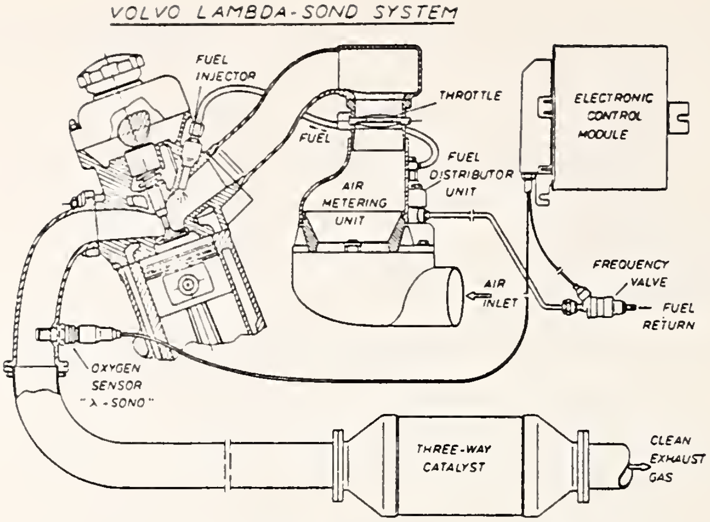
2.3.2 Fuel Injection Systems

The fuel injection systems presently in production or planned for introduction in the early 1980's are the intake manifold injection type, throttle-body injection type or the direct-cylinder injection type. Bendix (for GM) and Bosch (for VW and Volvo) presently produce versions of the multi-point intake manifold fuel injection system. Ford Motor Company has indicated that in 1981 it will introduce a single-point throttle-body fuel injection system and in the 1982-1985 time frame it will introduce a direct-cylinder fuel injection system (the stratified charge PROCO engine). These systems are different in implementation philosophy and are categorized by the following chart (Table 2-1). The differences among these systems relate specifically to two major categories, 1) location of the fuel metering valves with respect to the combustion chamber and 2) the method by which air mass flow is measured and thus by which the required fuel mass flow is determined.

The first major category is important, at least in determining to what extent the system provides improved cylinder-to-cylinder mixture distribution and improved dynamic response capability. A comparison of mixture distributions achievable with EFI (Electronic Fuel Injection) and carburetor systems has been done through steady-state dynamometer tests. The results have shown that under steady-state conditions, EFI systems are slightly better, but that under transient conditions, EFI systems have demonstrated significantly improved A/F ratio controllability to ± 3 percent of the desired value. These EFI systems have been of the multi-point intake manifold injection types (see Figures 2-10 and 2-11). In these systems there exists one fuel injection valve for each cylinder located in the intake manifold immediately adjacent to each engine cylinder intake valve. The cylinder-to-cylinder distribution is improved because the detrimental effects of intake

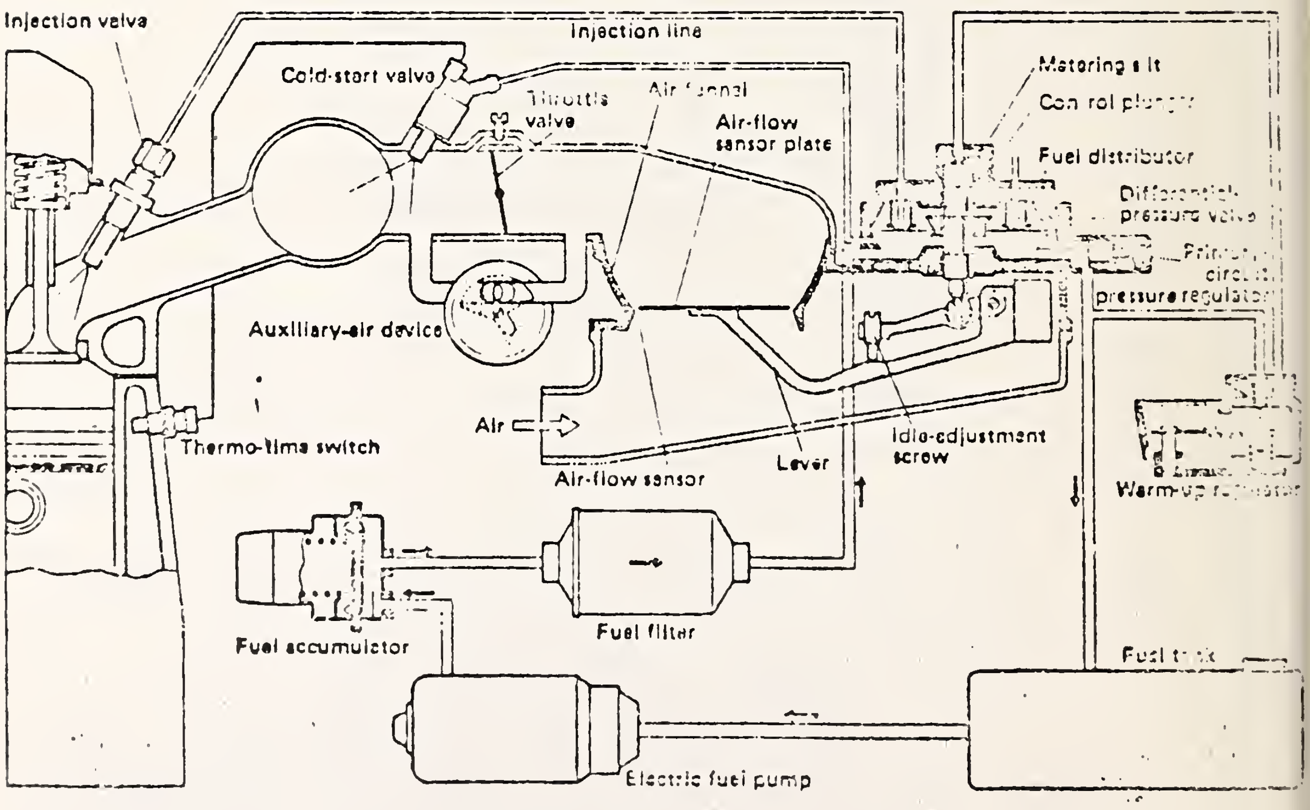
TABLE 2-1. FUEL INJECTION SYSTEM CATEGORIZATION

Fuel Injection System	Mechanically Controlled	Electronically Controlled	Mass Flow via Air Meter	Measures Air Mass Flow via Speed Density Computation
Bosch K-Jetronic Multi-point Intake Port Injection	✓		✓	
Bosch L-Jetronic Multi-point Intake Port Injection		✓	✓	
Bendix/GM System Multi-point Intake Port Injection		✓		✓
Ford's EFM Single-point Throttle Body Injection		✓		✓
Ford's PROCO Multi-point Direct Cylinder Injection		✓		✓



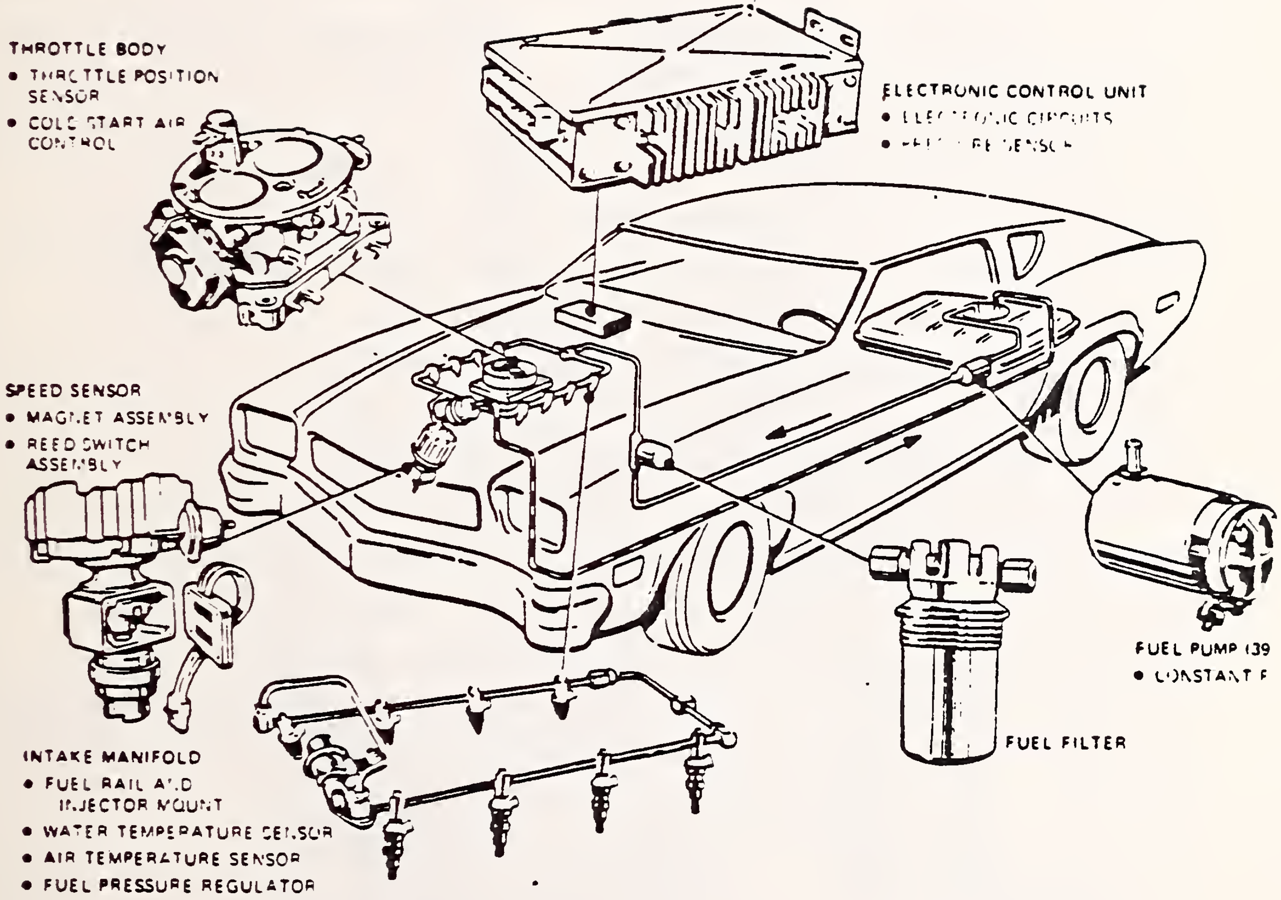
Volvo Lambda-sond system

Bosch K-Jetronic Fuel Injection System



Source: Reference 9.

FIGURE 2-10. VOLVO LAMBDA-SOND SYSTEM AND BOSCH K-TETRONIC FUEL INJECTION SYSTEM



Bendix Speed-density EFI System

Source: Reference 10.

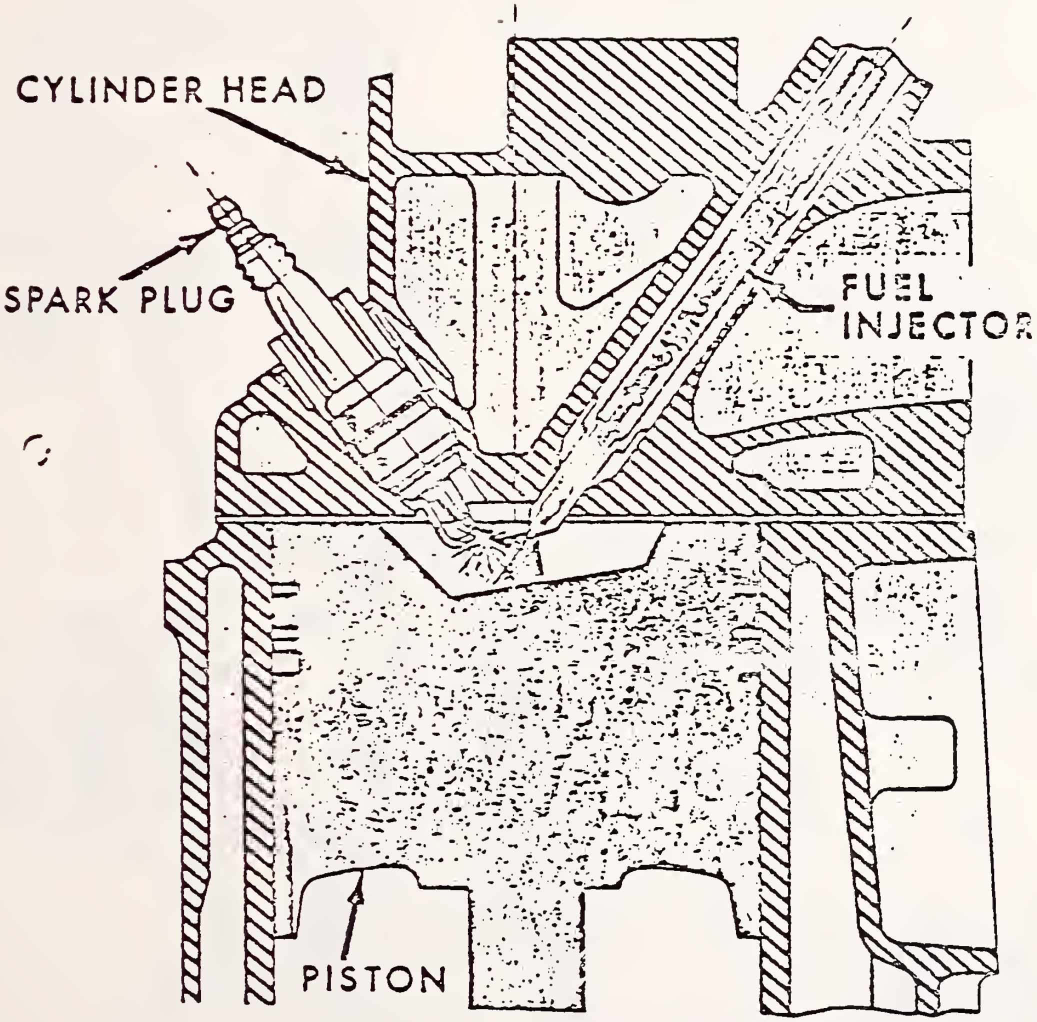
FIGURE 2-11. TYPICAL EFI VEHICLE INSTALLATION

manifold dynamics, as defined under carburetor systems (Section 2.4.1), have been reduced significantly. It is easy to see that the Ford PROCO system (see Figure 2-12), which utilizes direct cylinder injection for purposes of stratified charge (rich mixture near the spark plug but overall cylinder A/F ratio effectively leaned out to 19:1), should have extremely good cylinder-to-cylinder distribution and thus improved overall A/F ratio control. The Ford proposed throttle-body injection system (Electronic Fuel Metering (EFM), see Figure 2-13) lies somewhere between a carburetor and an EFI system in its fuel metering capability. It represents an improvement over a carburetor in its feed-forward fuel metering accuracy but still suffers from dynamic interactions with the intake manifold plenum, which increases A/F ratio spread to the combustion chambers. The introduction of EFM is seen as only a developmental step towards the introduction of the PROCO concept.

The second major category affects the accuracy of the electronic fuel control system and represents two different implementation philosophies. The first involves measuring air mas flow directly with an air flow meter upstream of the intake manifold. Examples of such meters are the Bosch Vane meter, Chrysler Swirl meter and the Ford Vortair meter. It is sufficient here to note that the output signals of these sensors are proportional to air mass flow (volumetric flow corrected for inlet pressure and temperature). The advantages of an air flow meter-based electronic fuel injection system are as follows (see Figure 2-14):

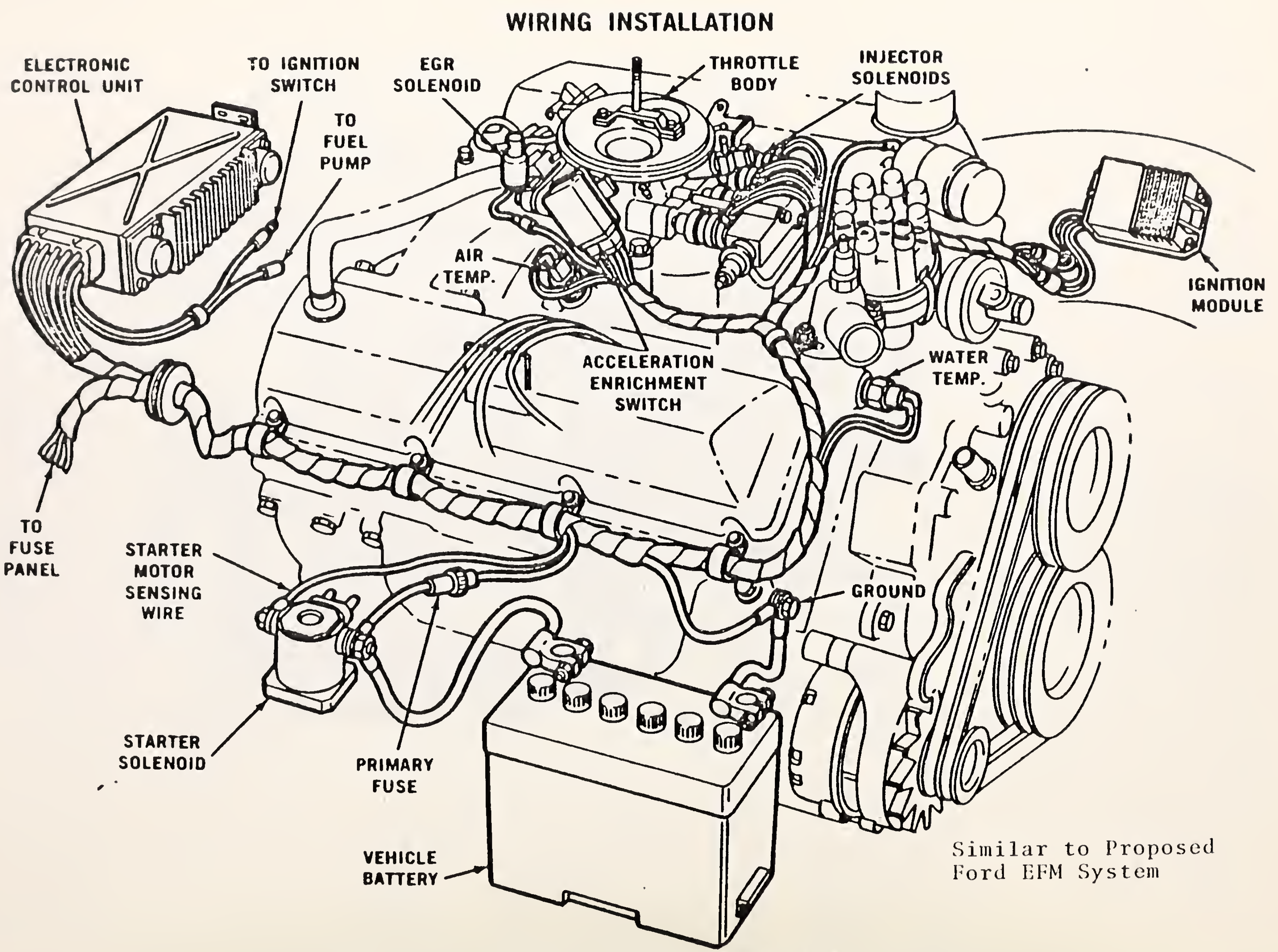
a) It measures air mass flow directly and proportions fuel mass flow accordingly.

b) Since it is upstream of the intake manifold, it represents a lead signal, during transients, on fuel demand (load compensation).



Source: Reference 11.

FIGURE 2-12. FORD PROCO



Similar to Proposed
Ford EFM System

FIGURE 2-13. WIRING INSTALLATION (SHEET 1 OF 2)

Proposed EFM SYSTEM COMPONENTS

Based on Bendix EFI
System Components

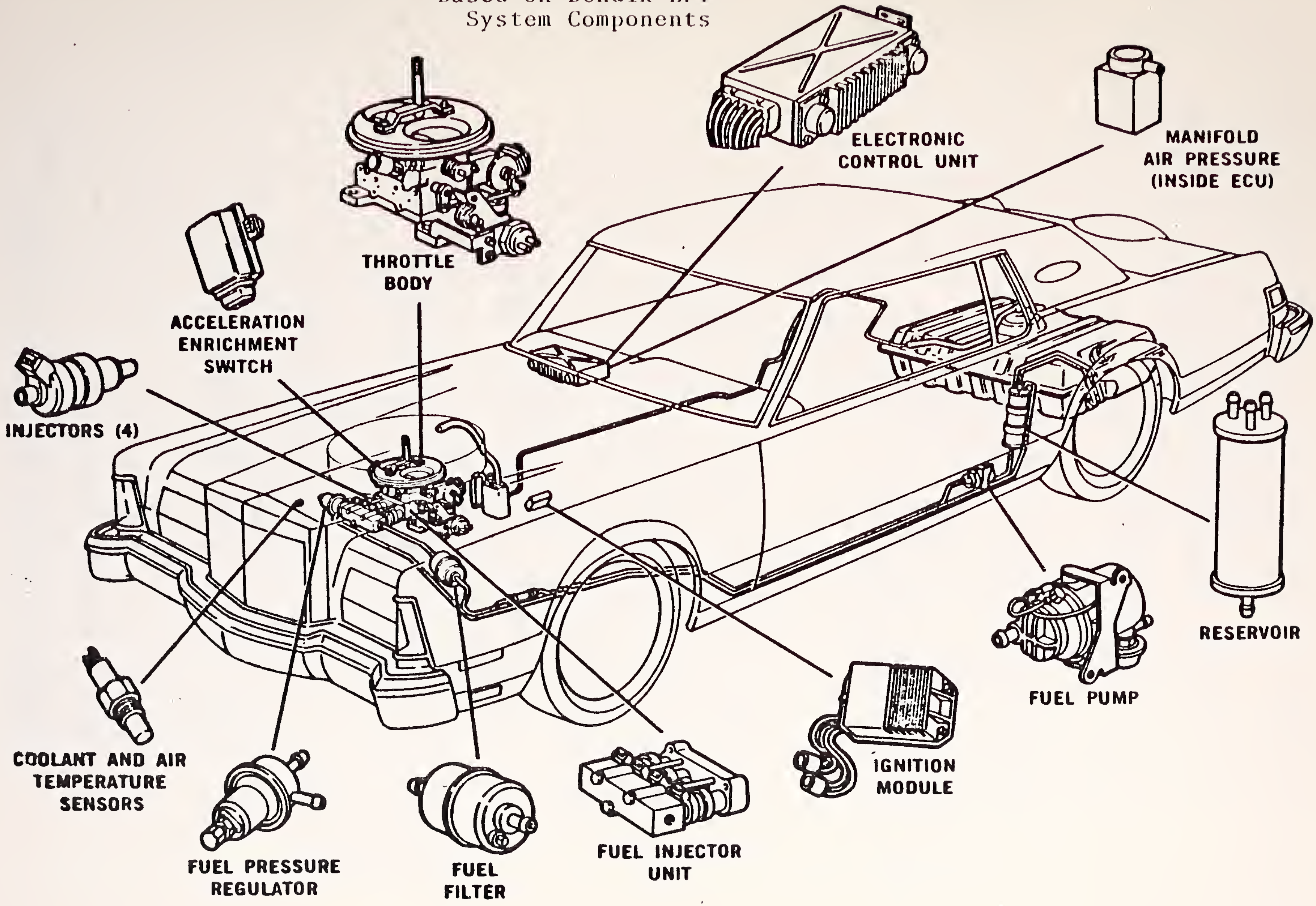
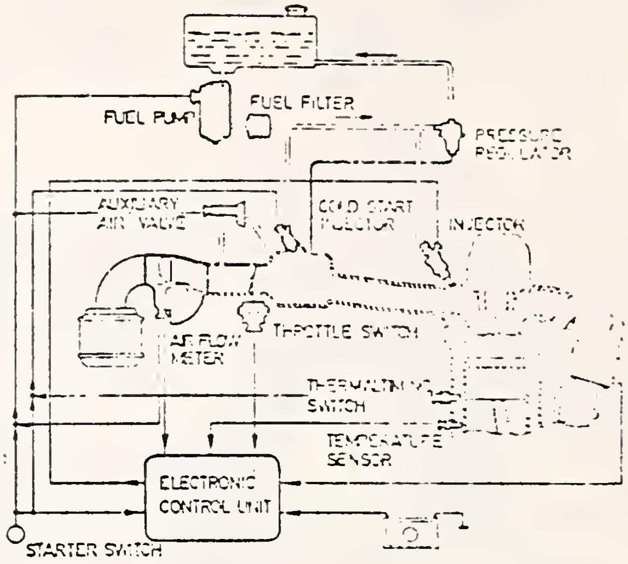
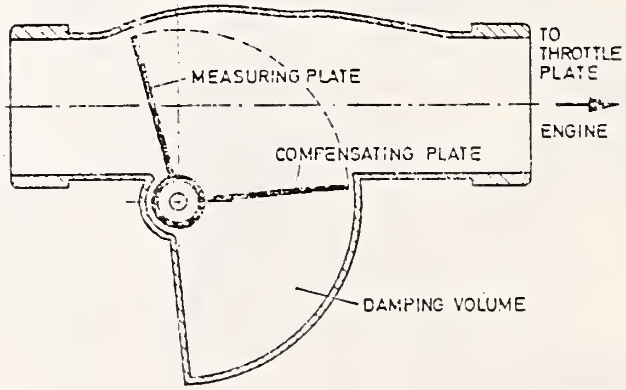


FIGURE 2-13. EFM SYSTEM COMPONENTS (SHEET 2 OF 2)



L-Jetronic with air flow metering



Cross-section of the air flow meter

Source: Reference 12.

FIGURE 2-14. L-JETRONIC WITH AIR FLOW METERING AND CROSS-SECTION OF THE AIR FLOW METER

c) It is sensitive to engine performance changes or degradation with mileage.

d) It is an independent measurement of air flow and therefore insensitive to errors in computation or calibration of the EGR mass flow system.

e) It is insensitive to engine-to-engine production variability.

The primary disadvantage of such a system is the additional cost and reliability of integrating a sophisticated electronic sensor into the overall system.

The second implementation philosophy involves measuring air mass flow via the indirect speed-density mass flow concept. This concept is best described by the formula:

$TMF = \rho . N_\nu . \frac{N}{2} . D$ where

TMF is total mass flow through an engine in lbm/min

ρ is the density of the gases in the intake manifold (air, fuel and EGR) in lbm/in^3

N_ν is the volumetric efficiency, or breathing efficiency, of the engine (dimensionless)

N is engine speed in RPM

D is displacement of the engine in in^3.

The computation of total engine mass flow rate can be done via analog or digital electronics. Fuel flow requirements can then be determined after some compensation for EGR mass flow is made. The primary advantage of such a system is its use of less costly sensors (engine speed, manifold pressure, inlet air temperature) which may already exist on the engine (assuming electronic spark control has been implemented). The disadvantages to a speed density based electronic fuel injection system are as follows (see Figure 2-15):

(1) requires density compensation for gases in the intake manifold which are varying vapor density ratios of air, fuel and EGR (Figure 2-16).

$$\lambda * 14.64 = \frac{A}{F} = \frac{\dfrac{P * \eta_v * N * D}{2} - \dfrac{K * A_t * P_E}{\sqrt{T_E}}}{A_D\,[PW - A_1] * \dfrac{RR}{2} * n * N}$$

numerator may be replaced with output signal of air mass meter

λ = equivalence ratio (air/fuel ratio divided by the stoichiometric air/fuel ratio)

$A/_F$ = the actual cylinder air/fuel ratio

14.64 = the assumed stoichiometric air/fuel ratio

η_v = the specific volumetric efficiency referenced to the pressure and temperature conditions in the intake manifold

N = engine speed in revolutions/min

D = total engine displacement in in^3

K $= \sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$ sonic mass flow constant for the EGR valve where R is the ideal gas constant and γ is the ratio of specific heats for exhaust gas

A_t = SONIC EGR VALVE throat area which is proportional to position

P_e = EGR valve upstream pressure

T_e = EGR valve upstream temperature

A_o = fuel delivery rate of a single injector in lbmass/sec

PW = pulsewidth/injector in seconds

A_1 = pulsewidth offset in seconds

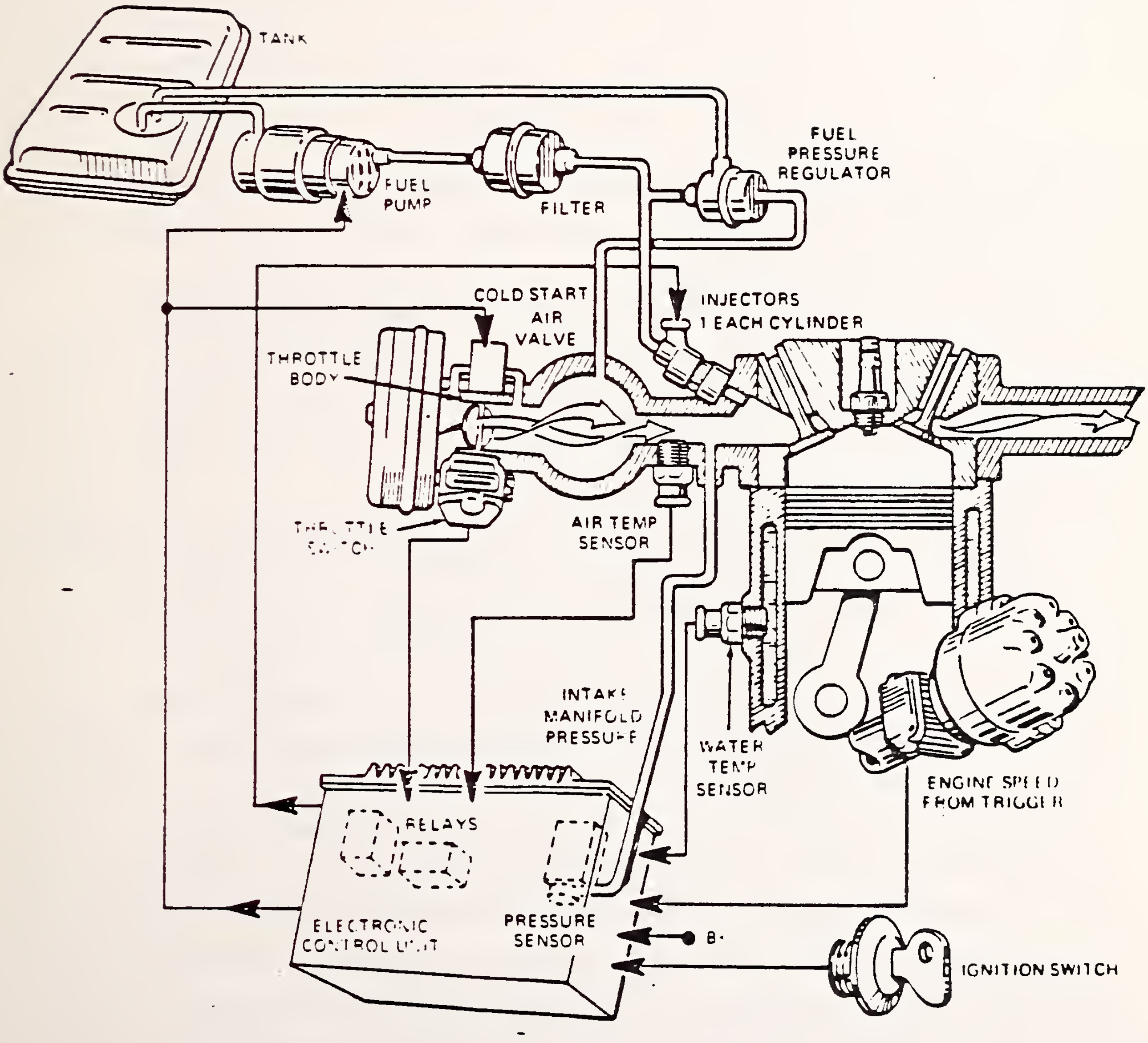
RR = # of times each injector is fired/cycle (repetition rate)

n = # of injectors

If parameters relating to EGR are available inputs to a controller, this control law is valid for throttle-body, intake-port or direct-cylinder injection systems.

Source: Reference 13.

FIGURE 2-15. CONTROL LAW FOR SPEED-DENSITY BASED EFI SYSTEMS WITH EGR CORRECTIONS



Source: Reference 10.

FIGURE 2-16. TYPICAL EFI SYSTEM INSTALLATION, SPEED-DENSITY BASED (Primary inputs are manifold pressure and engine speed)

2) requires compensation for EGR mass flow, which may not be known accurately, during engine transients or over long term mileage accumulations.
3) requires computation for engine volumetric efficiency which has a sensitivity to the following:

    engine-to-engine production variability
    engine degradation with mileage
    exhaust back-pressure
    altitude
    valve blow-by and timing
    engine speed and load

It should be noted that feedback control of A/F ratio (see Section 2.5) in combination with a speed-density based electronic fuel injection system, can be an extremely accurate fuel control system. This is due to an optimal mix of control system capability, i.e. the good dynamic response and distribution capabilities of an EFI system in combination with a feedback controller which can correct many of the disadvantages stated above.

Regardless of which control law implementation philosophy is utilized, the electronically controlled fuel injection system has demonstrated multiple advantages, such as: accurate mixture adjustment to every driving condition, particularly in transient periods; low throttling losses; flat torque/speed characteristics; reliable cold starting, good hot starting behavior; precise warm-up profiles; low tendency for vapor lock and low evaporative losses. This performance is accomplished by injecting fuel close to the intake valves or directly into the cylinders by electromagnetically actuated injection valves. Each is actuated once or twice per revolution of the camshaft, and the fuel quantity delivered is proportional to or controlled by the opening period of the solenoid valves. Emissions and fuel efficiency are extremely sensitive to the control of fuel quantity, ignition timing and exhaust

gas recirculation. Electronic control offers particularly good possibilities to correlate all these parameters with each other in a highly interactive real-time sense.

2.4 CATALYST AND SECONDARY AIR SYSTEMS

Catalyst systems have been used in the control of exhaust emissions since 1975. There have been basically two types used in production to date, the conventional oxidizing catalyst (COC) and the three-way catalyst (TWC). Domestic manufacturers have almost exclusively used COC canisters, with TWC canisters showing up on some California models and on the Volvo lambda-sond system. Since the COC canister is an oxidation catalyst only, it is usually implemented with a secondary air injection system that pumps excess air just ahead of the canister to insure sufficient free oxygen for complete oxidation of HC and CO species.

The COC system will also be applicable to future engine/emission systems which are designed to operate at lean air/fuel ratios (e.g. Ford PROCO and Chrysler's Lean-Burn System). However, if accuracy of A/F control is not good enough to allow very lean operations, additional NO_x control systems such as EGR or spark retard will be required. The TWC system is capable of conversion of all three regulated emission species (oxidation of HC and CO and reduction of NO_x but requires operation at precisely the stoichiometric A/F ratio.

In the future, the three-way catalyst may be used in conjunction with a conventional catalyst for additional oxidation of HC and CO. In this configuration, secondary air injection would occur between the TWC canister and the COC canister. Emphasis is given here to the TWC because the requirements it places on the engine control system will have a significant impact upon the use of electronics.

The three-way catalyst itself is visually identical to the oxidation catalyst. It may contain a ceramic monolithic (honeycomb) support structure, as in the Ford catalyst, or thousands of pellets, as in the GM catalyst. The support structure (whether pellets or honeycomb) is coated with a finely divided alumina washcoat which permits the active catalytic elements to be dispersed over a very large surface area (hundreds of square meters per gram of washcoat).

There is some similarity in the active elements of the three-way and oxidation catalysts: both contain a precious metal, such as platinum, which performs the bulk of the oxidation reaction. In addition, the three-way catalyst contains other active elements such as rhodium for NO_x reduction and base metals for oxygen storage and other chemical reactions which permit HC and CO oxidation to occur for short time periods in the absence of sufficient free oxygen (see Figure 2-17).

Electronic controls are not used to actuate catalysts directly since there are no electromechanical systems or sensors specifically involved in internal catalytic operations. Instead, electronics are used to control external variables (inputs to the catalyst system) that improve catalyst performance both instantaneously and over hundreds of hours of operation. The conversion efficiencies of catalysts are particularly sensitive to temperature, space velocity, mean A/F ratio and variations of A/F ratio with time. Figure 2-18 shows the typical conversion efficiencies for a three-way catalyst. Catalytic control of HC and CO emissions requires an oxidizing atmosphere in the exhaust which is typically available with lean A/F ratio operation or secondary air injection. Catalytic control of NO_x emissions requires a reducing atmosphere in the exhaust which is typically available with rich A/F ratio operation. However, at the chemically correct mixture (stoichiometry) a very narrow A/F ratio window exists where the conversion efficiencies for HC, CO and NO_x simultaneously exceed 80%. This implies that the design requirement for TWC-based emission control systems is that the A/F ratio be controlled to within this window ($\pm$1% of Stoichiometry).

Previously, this window was thought to define the required accuracy of the vehicles' fuel contol system. Considering that the window width at 80% conversion is generally less than 0.15 ratios, the task of controlling A/F ratio within this narrow range over all engine conditions seemed hopeless. However, several factors modify this picture significantly: time-varying A/F ratio affects catalyst performance in a way not predictable from studying

Oxidation in the presence of O_2

(1) $C_mH_n + (M + N/4)O_2 \rightleftharpoons mCO_2 + N/2\ H_2O$

(2) $CO + \frac{1}{2}O_2 \rightleftharpoons CO_2$

(3) $H_2 + \frac{1}{2}O_2 \rightleftharpoons H_2O$

Oxidation in the presence of water

(4) $CO + H_2O \rightleftharpoons CO_2 + H_2$ (water gas shift)

(5) $C_mH_n + 2mH_2O \rightleftharpoons mCO_2 + 2(m + n/4)H_2$ (Steam reforming)

Reduction of NO

(6) $NO + CO \rightleftharpoons \frac{1}{2}N_2 + CO_2$

(7) $2(m + n/4)NO + C_mH_n \rightleftharpoons (m + n/4)N_2 + n/2H_2O + mCO_2$

(8) $NO + H_2 \rightleftharpoons \frac{1}{2}N_2 + H_2O$

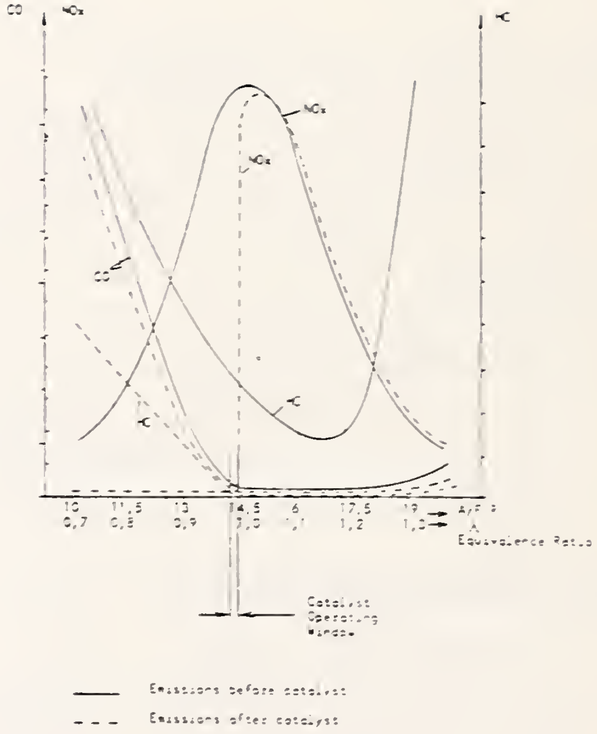
Ammonia Formation and Its Fate

(9) $NO + 5/2H_2 \rightleftharpoons NH_3 + H_2)$

(10) $3NO + 2NH_3 \rightleftharpoons 5/2N_2 + 3H_2O$ (desirable)

(11) $NH_3 + 5/4O_2 \rightleftharpoons NO + 3/2H_2O$ (undesirable)

FIGURE 2-17. SOME OF THE CHEMICAL REACTIONS OCCURRING IN THREE-WAY CATALYSTS



Source: Reference 9.

FIGURE 2-18. EXHAUST EMISSIONS WITH THREE-WAY CATALYST

Figure 2-18, and the mean A/F ratio of an engine may change in a manner which favors conversion of the pollution component which is most important at that moment (A/F enrichment during power modes tends to favor NO_x conversion at the time NO_x is being produced in the greatest quantities).

The first of these factors is discussed in some detail here because it impacts fuel control accuracy requirements. Figure 2-19 shows the conversion efficiency of a TWC catalyst which had a periodic sawtooth variation of A/F ratio superimposed on a mean value of stoichiometry. The frequency of variation is 1.0 Hz. Comparing Figure 2-19 with 2-18 shows that the time-varying A/F ratios moves the peak NO_x conversion to richer A/F ratios and gives significant NO_x conversion lean of stoichiometry. If the total emission control system was satisfied by 80% CO conversion, 93% HC conversion and 60% NO_x conversion, the control requirement would be a mean A/F ratio within a .3 band about stoichiometry and a varying amplitude of A/F ratio of ± 1.0 at a frequency of 1 Hz or higher. This is precisely the phenomenon that has led to the implementation of electronic feedback fuel control via the feedback carburetor. This widening of the TWC window gives some justification to using a carburetor instead of the more costly and more accurate EFI system. Feedback control is discussed in detail in Section 2.5.

Finally, one should realize the significance of temperature on catalyst performance. Catalyst light-off (where the catalyst begins to convert effectively) occurs at about 300°C and is completely up to the temperature at about 600°C. The Ford EEC-II system (due in 1979) will electronically control secondary air for optimum catalyst performance. The computer-implemented strategy could dump the air into the atmosphere until the TWC/COC system is up to 300°C, then electromechanically switch the air to upstream of both catalysts (since during the initial part of the CVS-C/H test very little NO_x is formed, both catalysts can be used for oxidation, and the extra air will help). Then for the remainder of the test the air is between the catalysts using the TWC for NO_x control.

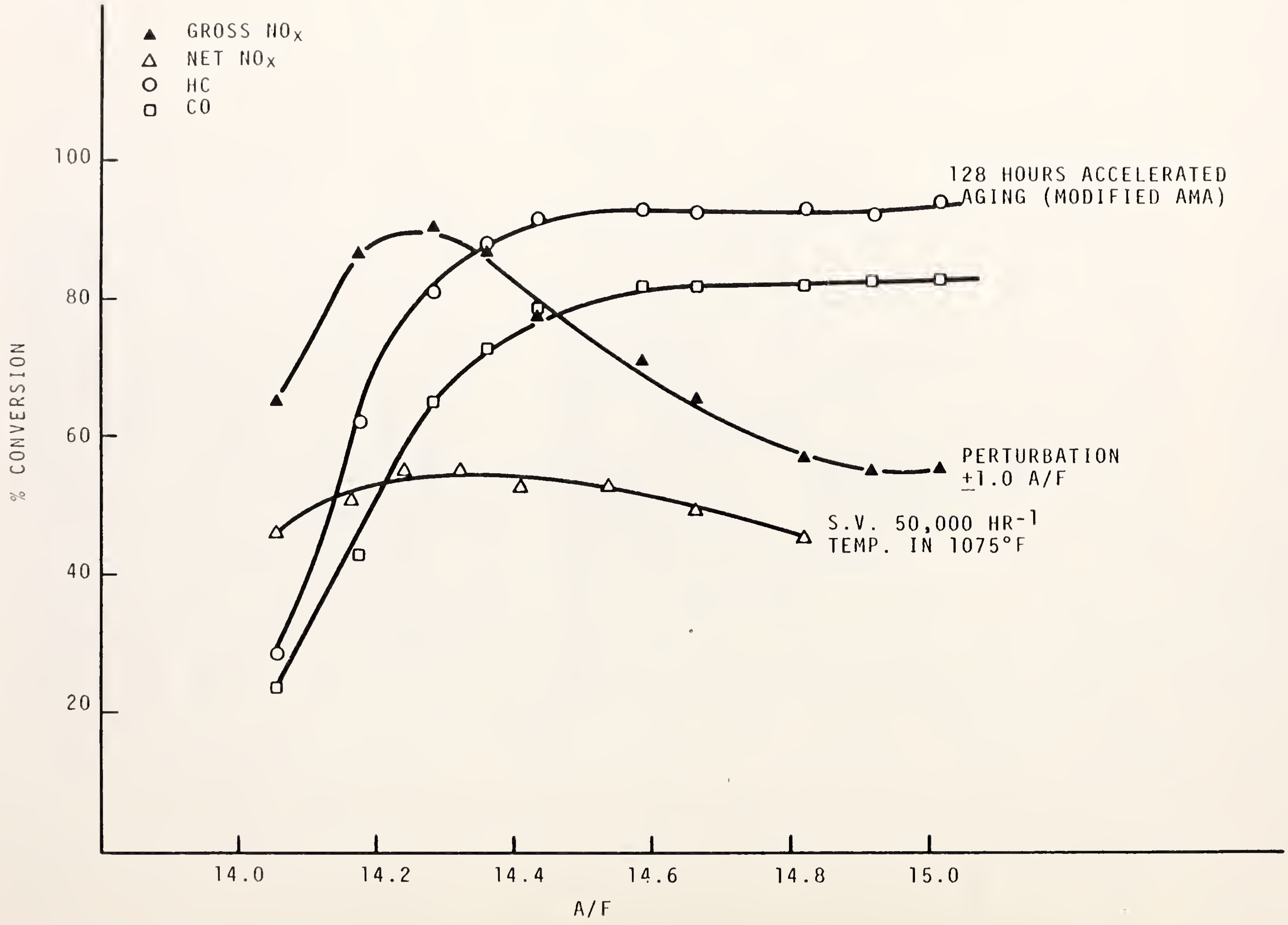


FIGURE 2-19. ENGELHARD 19D Pt/Rh = 11/1,40 gm/ft^3

2.5 FEEDBACK CONTROL SYSTEMS

As indicated in the previous section, systems that rely on the use of the three-way catalysts require precise fuel metering at stoichiometry for simultaneous control of HC, CO and NO_x emissions. This requirement has spurred the development of feedback correction of carburetors and EFI based systems. The first three-way catalyst and feedback controlled fuel injection (Bosch K-jetronic) system was introduced by Volvo on their 1977 California 130 CID engines (Ref Section 3.). General Motors certified a closed-loop, carbureted, three-way catalyst system on their 1978 California 151 CID engines, and Ford Motor Company certified a closed-loop, carbureted, three-way catalyst system on their 1978 California 140 CID engines (Ref. Section 3.). Ford has indicated that in 1979 it will introduce EEC-II, which will electronically control spark, EGR and A/F ratio simultaneously (via a feedback carburetor) on its 351 CID V-8 engines. It is anticipated that larger displacement engines will require dual bed catalyst systems, a TWC and a COC for additional cleanup of HC and CO emissions.

Section 2.3 outlined in detail the relative fuel metering capability of carburetors, intake manifold EFI and direct-cylinder EFI systems. Also described were the different EFI implementation philosophies represented by air mass flow meters and speed density calculations. The carburetor system has been described as a 10-15 percent device, the speed density as a 5-10 percent device and the air mass meter system as a 3-5 percent device. Each of these systems has errors that can be reduced via feedback control of A/F ratio. Therefore, the strategy is to calibrate a carburetor or EFI system to the "best" possible open-loop performance under standard conditions and then utilize a feedback fuel control concept to correct the feed-forward system errors.

Figure 2-20 describes in general the key elements of the feedback control system. The exhaust gas sensor is the component that provides the fuel control system with the capability of closing the loop on air-fuel ratio. The zirconia dioxide sensor is very sensitive to the partial pressure of oxygen in the exhaust stream

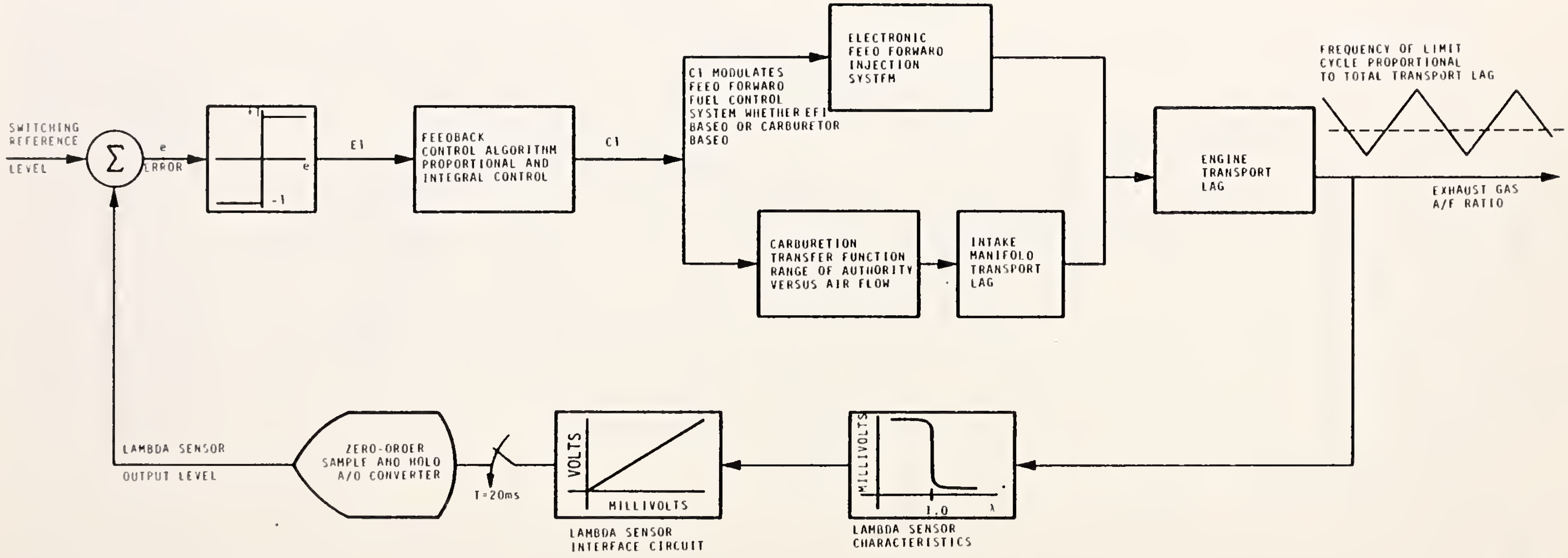


FIGURE 2-20. BLOCK DIAGRAM OF FEEDBACK FUEL CONTROL SYSTEM UTILIZING DIGITAL ELECTRONIC TECHNIQUES

(referenced to atmospheric O_2 levels). As the A/F ratio passes through stoichiometry, the partial pressure of oxygen in the exhaust gas changes abruptly, resulting in a step change in the output voltage of the sensor. This voltage signal is an input to the electronic control logic, which in turn, modulates the fuel supply system. Regardless of which fuel supply system is used, electronic feedback control of the A/F ratio will improve the accuracy and controlability of the A/F ratio delivered to each cylinder over that of a conventionally equipped engine. The advantages of feedback A/F ratio control for TWC based systems which are common to all or unique to carburetors and each EFI system are as follows:

a) compensates for variations in fuel composition as characterized by the hydrogen carbon mole ratio. Stoichiometry can vary by several tenths of a ratio for commercially available fuels.

b) compensates for manufacturing tolerances and errors in calibration of carburetors, fuel injectors and air flow meters both initially and as these systems degrade over time.

c) compensates for volumetric flow characteristics of carburetors by correcting for air density changes that occur with inlet air temperature and barometric pressure.

d) compensates for variances in the empirically derived volumetric efficiency which is the basis for speed density EFI or EFM. This includes the variability in the given test engine, the manufacturing variability among production engines, the sensitivity to changes in exhaust backpressure with altitude, and the variability in engines as they degrade with mileage accumulation.

e) compensates for long-term drifts or variances in other sensors or components that make up the feed-forward or feedback control system (e.g the vacuum regulator and modulator on feedback carburetors or the manifold absolute

pressure sensor on speed-density EFI systems).

f) compensates for dynamic errors associated with the interactive aspects of EGR and the intake manifold plenum.

As can be seen, feedback control of A/F ratio is used to compensate for many of the characteristics of primary fuel delivery systems which cause them to make less than optimum use of the three-way catalyst. The loss of open-loop control of A/F ratio will result in losses of conversion efficiency with the TWC. If the engine control system does not make maximum use of the TWC, then spark retard and EGR modifications will be required, resulting in a loss of fuel efficiency.

A question that should be asked is what advantage does an EFI fuel delivery system have over a carbureted or throttle-body injection system if feedback control of A/F ratio in combination with a TWC is used. As outlined above, feedback control compensates for shifts in open-loop calibration, variability in manufacturing, and long-term slowly varying drifts due to the aging of components or to a change in atmospheric conditions. However, as Figure 2-20 indicates, the output signal of the sensor is basically a switch yielding a high voltage for exhaust mixtures rich of stoichiometry. This causes the electronic controller to drive lean, and a low voltage for exhaust mixtures lean of stoichiometry causes the controller to drive rich. Since no absolute amplitude of A/F ratio information is given, the closed-loop control system is basically, in control system terminology a "bang-bang limit-cycle system," i.e., even under steady-state conditions the A/F ratio will be constantly varied to the limit cycle amplitude. Therefore, the dynamic response of the closed-loop system (a measure of feedback systems speed in correcting for an open-loop error) is proportional to the frequency of the limit cycle; the frequency of the limit cycle is inversely proportional to the total open-loop transport lag (the time it takes for a change in fuel delivered to be sensed at the sensor).

It is also important to realize that both the dynamic response of the closed-loop system and the amplitude (excursions from stoichiometry) in A/F ratios of the limit cycle are proportional to the closed-loop gain of the feedback control system. The higher the gain, the faster the response and the larger the amplitude of limit cycle.[10] The transport lag of an EFI system is of the order of .05 to .3 seconds (3 engine revolution) while the transport lag of a feedback carburetor can be from .2 to 1.5 seconds depending on intake manifold volume, dynamic response of the carburetor modulation system and location of the feedback sensor in the exhaust stream. An EFI system does not suffer from the transport lag introduced by vacuum modulation of a metering rod at the carburetor (which has already been shown to be a slow device) or by the fuel storage and discharge phenomenon of the intake manifold plenum.

It is also important to note that poor closed loop dynamic response (associated with the long transport lags of throttle-body fuel metering) requires that the dynamic flow curve (air-fuel ratio delivered versus air flow) at a given closed-loop setpoint be extremely flat. For example, given an electronic closed-loop carburetor system where A/F ratio modulation is accomplished via a tapered rod within the main metering orifice, then for a given tapered rod position the same air-fuel ratio should be delivered over the total air flow range (from idle to the end of part throttle). This action minimizes the air-fuel ratio disturbances caused by engine throttling, which the slow feedback loop has to correct. This flatness requirement for throttle-body fuel metering systems is difficult to maintain over the entire correction range of the feedback loop.

Therefore, the significance of a feedback EFI system is that it takes full advantage of the dynamic response capability of the feedback control loop. This short term transient control modulates the open-loop system at a very high frequency, resulting in a minimum A/F ratio excursion from stoichiometry in the the amplitude of limit cycle, maximum close-loop gain and very tight control

of the mean exhaust A/F ratio. Tests that have been done on the Volvo lambda-sond system have indicated a $\pm 1.5\%$ control of exhaust A/F ratio about stoichiometry during the worst engine transient portions of the Federal Test procedure (see Figure 3-11).[9] It should be noted, however, that such a system has not been produced on a large V-8 engine.

In V-8 and V-6 engines, the exhaust stream is divided into a left and right bank. The sensor must be located near the exhaust flange to minimize the transport lag and to keep the sensor up to temperature. Therefore, extremely good bank to bank distribution is required, or independent closed-loop control about each bank might be necessary. It is believed that EFI systems have better bank to bank distribution characteristics than carburetors, which may result in less complicated closed-loop hardware. Regardless of the fuel delivery system utilized, a feedback sensor may be required in each exhaust bank to insure maximum TWC efficiency.

Feedback control of other key engine variables has been relatively limited, thanks primarily to the lack of sensors. Feedback control of EGR was introduced in Section 2.2, but that system was closed-loop about EGR valve position. The closed-loop A/F ratio system is an attempt to correct the inaccuracy of EGR levels actually delivered to the combustion chamber. Closed-loop spark control has been developed for turbocharged engines via a sensor (e.g., an accelerometer) which senses the knock-limit spark advance. This system does not allow closed-loop setpoint control to spark advances other than knock-limits. Further research into the nature of these errors may lead to an improvement of the present open-loop approach to EGR and Spark control.

2.6 TRANSMISSION CONTROL

As might be expected, the automobile engine is not the only component of the vehicle that has the potential for yielding improved fuel efficiency via more accurate control of its primary function. The automatic transmission offers fuel economy advantages

by 1) reducing or eliminating hydraulic torque converter slip and 2) matching transmission gear ratios more closely to engine operation.

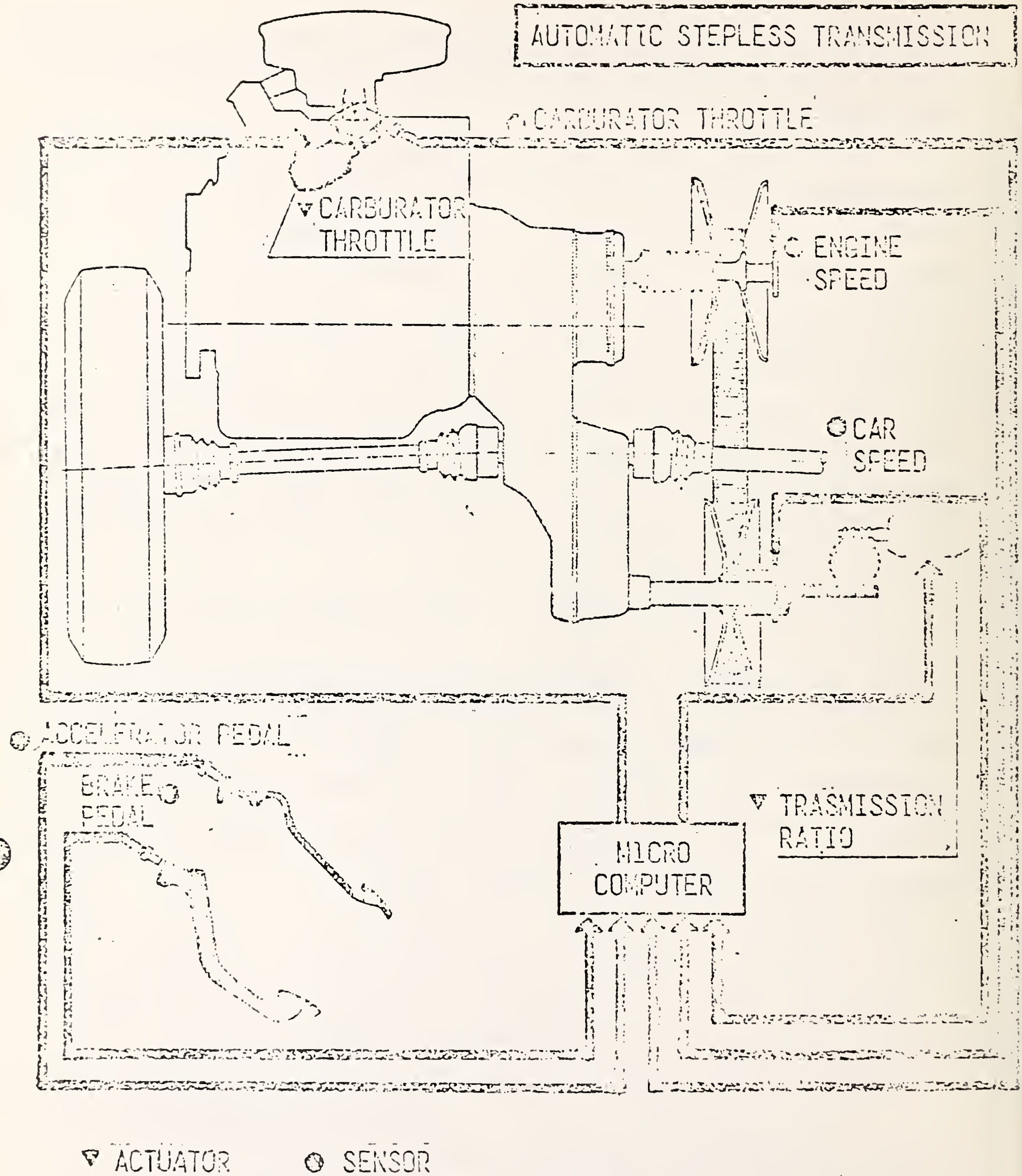
Chrysler has demonstrated the advantages of the first technique with the introduction (1978) of its lock-up torque converter. This implementation eliminates torque converter slip by imposing a lock-up clutch mechanism which results in direct-drive from engine to drive shaft. The design, however, accomplishes this only in third gear (highest gear) and above an engine speed of 850 RPM. The results are, respectively, a 4 percent and 6 percent improvement in fuel economy on EPA urban and highway test.[14] Arthur D. Little[15] has done research on implementing torque converter lock-up in second, third, and fourth gears and has shown as much as a 14 percent improvement (under conditions of no emission constraints).

Fiat,[16] on the other hand, has an extensive research program utilizing the second technique. Since the internal combustion engine can furnish the same output torque at different RPM rates and throttle positions (if maximum performance is not the requirement), then the engine can be so controlled as to generate the same acceleration at a given engine speed through different transmission gear ratios, of which only one minimizes fuel consumption. Fiat has addressed this issue with basically two types of transmissions (see Figure 2-21):

a) DVT (Discrete variable transmission); 5 discrete gear ratios with shifting provided by multidisc clutches; starting-up by centrifugal clutch (one 4-gear version exist with lock-up in the three highest gears).

b) CVT (Continuously variable transmission); single V-belt with centrifugal clutch. Pulley's displacement and thus transmission ratio are controlled by a D.C. motor.

In both systems the accelerator pedal is no longer mechanically linked to the throttle plates. The accelerator pedal position is an input to an electronic control system and is used as an



Source: Reference 16.

FIGURE 2-21. AUTOMATIC STEPLESS TRANSMISSION

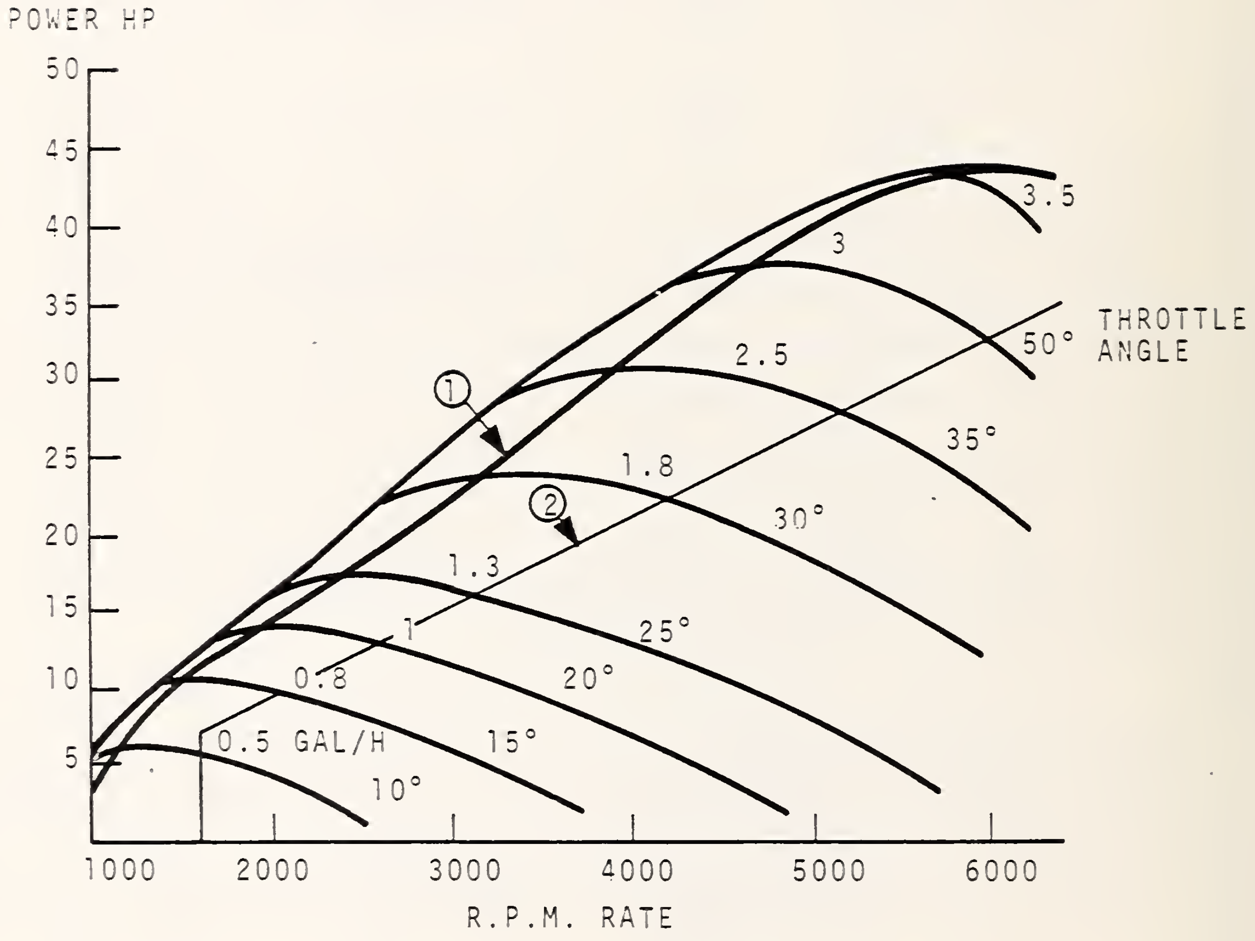
indication of the power demanded by the driver. The electronic control unit is microprocessor based primarily because the control system is required to perform a three-dimensional linear interpolation algorithm that determines the ideal throttle angle (Ref. Figure 2-22) for the given engine RPM and power level demanded. The throttle angle desired is compared to the actual throttle angle (via a feedback potentiometer), and if an error exists, the electronic module actuates a D.C. motor that moves the throttle plates to the desired setting.

The significant issue here is the decoupling of the throttle plates from the accelerator pedal, thus putting control of the engine/transmission system entirely within the computer. The computer can control the system over the optimal trajectory. The engine operating point as defined above (throttle angle desired, power demanded, engine RPM) is compared to the least-fuel-consumption-engine-schedule (see Figure 2-22) and if this point a) lies near, no change in gear ratio b) lies to the left, a higher gear ratio is required or c) lies to the right, a lower gear ratio is required in order to move into the optimal band. This schedule is achieved exactly by the CVT transmission and approximated by the DVT transmission.

In addition to accelerator pedal position, throttle plate position and engine RPM, the transmission input shaft RPM and vehicle speed are required controller inputs to make downshifts and upshifts smoothly. The results to date on a 4-cylinder -903 CC engine in a 1750 lbs inertial weight vehicle are as follows:[16]

	City		HW		Comb	
Transmission Type	MPG	Δ%	MPG	Δ%	MPG	Δ%
Conventional	27.8	-	-	-	31.0	-
DVT	31.4	+13%	40.6	+12%	35.0	+13%
CVT	32.7	+18%	38.8	+7%	35.2	+14%

These results are very promising for the potential of total electronic control of engine/transmission systems, but more research is required to determine whether these results may be extrapolated to vehicles with greater inertial weight and larger engine/trans-



1 Minimum consumption line where the motor is used by automated stepless transmission (CVT).

2 Right limit of the area when the motor is used by automated stepped transmission (DVT).

Source: Reference 16.

FIGURE 2-22. POWER VERSUS RPM RATE, STEPLESS (CVT) AND STEPPED (DVT) TRANSMISSION

mission configurations. The work quoted earlier by Arthur D. Little indicates that improvements of this order are possible on larger, domestically produced vehicles, but emission data on these engines is limited.

2.7 ADVANCE CONCEPTS IN CALIBRATION

What has been reviewed to this point has been primarily engine and powertrain systems represented by hardware mechanizations which are modified on an individual basis to make use of the capabilities of electronic control systems. Until very recently the task of calibrating a given engine/powertrain configuration was simply an iterative procedure of testing, adjusting the carburetor or the initial timing and then re-testing.

Needless to say, this procedure could be time-consuming and very costly. As the number of control variables increased and the sophistication and complexity of emission control systems increased, the task became overwhelming. The engine/powertrain/aftertreatment mechanization and all of the other emission subsystems had to be treated as a total system and a methodical systems approach was needed in order to define an optimum calibration or control algorithm for a given emission constraint that would yield a minimum in fuel consumption.

The computational powers of large scale computers were used in addressing this problem and several techniques have been published.[2,3,4] These concepts are extremely important because they emphasize the interactive nature of emission control and represent a way in which maximum efficiency of a given hardware configuration can be achieved.

The development of this advance systems approach to emission control divides basically into two philosophies, that represented by Auiler[3] and Rishavy[2] et al. and that represented by Dohner.[4] The complex interaction of engine control variables (spark timing, EGR, air/fuel ratio, secondary air injection, transmission ratio, etc.) and their impact on emissions and fuel consumption as a function of engine state variables (engine speed, intake manifold

pressure, coolant temperature, inlet air temperature, barometric pressure, vehicle speed, EGR rate, engine torque, etc.) makes it impossible to intuitively determine the direction and magnitude of changes in all control variables simultaneously to achieve the required emission constraint at minimum fuel consumption. The relative capabilities of the two philosophies to address this control problem is discussed in the following paragraphs.

Auiler,[3] Rishavy[2] and others have addressed the system-wide control problem by utilizing the following procedure:

1) Define for a given engine/vehicle configuration (horsepower, inertial weight, transmission and rear axle ratio) via a powertrain simulation, the speed-load-trajectory required to accomplish the FTP schedule. The total time at each speed-load point is also an output (Ref. Figure 2-23).

2) Based on the <u>time</u> profiles, determine a small set (approx. 10) of engine speed-load points which approximates the FTP schedule.

3) Given this set of points, run an exhaustive steady-state dynamometer experiment collecting data on emissions, fuel consumption, and all engine state variables while varying all engine control variables. The experimental set-up should include all emission subsystems applicable to the given engine.

4) This data is then analyzed for the optimum control law as a function of engine state variables. Auiler applies a resource allocation algorithm using dynamic programming and Rishavy applies a simplex linear programming algorithm.[2,3]

Figure 2-24 is an example of the output from this procedure. Some of the work done in this area has included catalyst conversion characteristics, but no data has been presented utilizing the variable transmission ratio concept. The advantages in using this procedure are 1) it defines the optimal control trajectory for a given engine/emission system configuration; 2) since the data is

305 V8 - A3 - 4500 LB INERTIA WT - 2.56 AXLE

ENG TRQ LEVELS:		ENG SPD LEVELS: 0	500	700	900	1100	1300	1500	1700	1900	2100 2300	ROW TOTALS:
-50.0-	-40.0:	0.15	.	.	.	.	.	.	.	.	.	0.15
-40.0-	-30.0:	0.15	.	.	.	.	.	.	.	.	.	0.15
-30.0-	-20.0:	0.15	.	.	.	.	14.30	6.67	.	.	.	21.11
-20.0-	-10.0:	0.15	.	.	21.25	68.12	43.89	4.78	.	.	.	138.19
-10.0-	0.0:	0.15	.	2.11	84.35	18.00	6.87	11.44	1.00	.	.	123.92
0.0-	10.0:	0.15	.	429.74	109.00	39.12	17.68	3.64	0.86	.	.	600.20
10.0-	20.0:	0.09	0.71	436.47	184.26	76.11	11.46	9.61	6.02	.	.	724.73
20.0-	30.0:	6.18	99.09	164.60	162.02	109.62	9.56	44.11	51.63	.	.	646.82
30.0-	40.0:	0.87	2294.21	90.56	128.81	112.28	47.16	80.51	49.40	.	.	2803.79
40.0-	50.0:	1.70	97.80	13.29	165.98	132.73	114.81	124.81	61.24	3.64	.	716.00
50.0-	60.0:	0.94	20.17	26.17	72.13	335.47	165.80	106.15	114.63	30.09	.	871.56
60.0-	70.0:	0.04	5.28	28.11	57.61	265.88	125.84	101.25	152.80	70.32	.	807.12
70.0-	80.0:	.	1.02	24.88	124.66	221.24	207.42	183.00	202.57	186.51	.	1151.29
80.0-	90.0:	.	.	30.33	47.30	194.31	239.04	255.71	163.29	111.82	.	1041.82
90.0-	100.0:	.	.	30.57	54.63	147.79	198.52	233.04	91.01	60.19	.	815.75
100.0-	110.0:	.	.	14.25	60.06	150.83	165.35	119.69	54.74	118.04	.	682.95
110.0-	120.0:	.	.	3.64	41.02	80.14	117.87	89.21	73.31	62.67	0.77	468.64
120.0-	130.0:	.	.	2.70	34.34	21.14	100.09	87.68	75.42	45.59	1.79	368.76
130.0-	140.0:	.	.	1.47	18.54	10.69	29.53	79.84	65.44	15.34	1.22	222.08
140.0-	150.0:	.	.	0.36	17.35	3.84	4.88	29.78	65.91	21.03	0.82	143.98
150.0-	160.0:	.	.	.	3.66	0.86	1.79	5.67	50.79	7.78	0.31	70.85
160.0-	170.0:	.	.	.	1.63	1.33	0.69	3.90	7.03	3.05	0.63	18.26
170.0-	180.0:	.	.	.	0.90	0.02	0.76	11.03	8.85	1.66	.	23.22
180.0-	190.0:	.	.	.	.	.	.	.	10.83	1.74	.	12.57
190.0-	200.0:	.	.	.	.	.	.	.	5.52	1.29	.	6.80
200.0-	210.0:	.	.	.	.	.	.	.	.	.	.	0.00
210.0-	220.0:	.	.	.	.	.	.	.	.	.	.	0.00
220.0-	230.0:	.	.	.	.	.	.	.	.	.	.	0.00
230.0-	240.0:	.	.	.	.	.	.	.	.	.	.	0.00
240.0-	250.0:	.	.	.	.	.	.	.	.	.	.	0.00
250.0-	260.0:	.	.	.	.	.	.	.	.	.	.	0.00
COLUMN TOTALS:		10.72	2518.28	1299.24	1389.49	1989.53	1623.31	1591.54	1312.30	740.75	5.55	12480.70

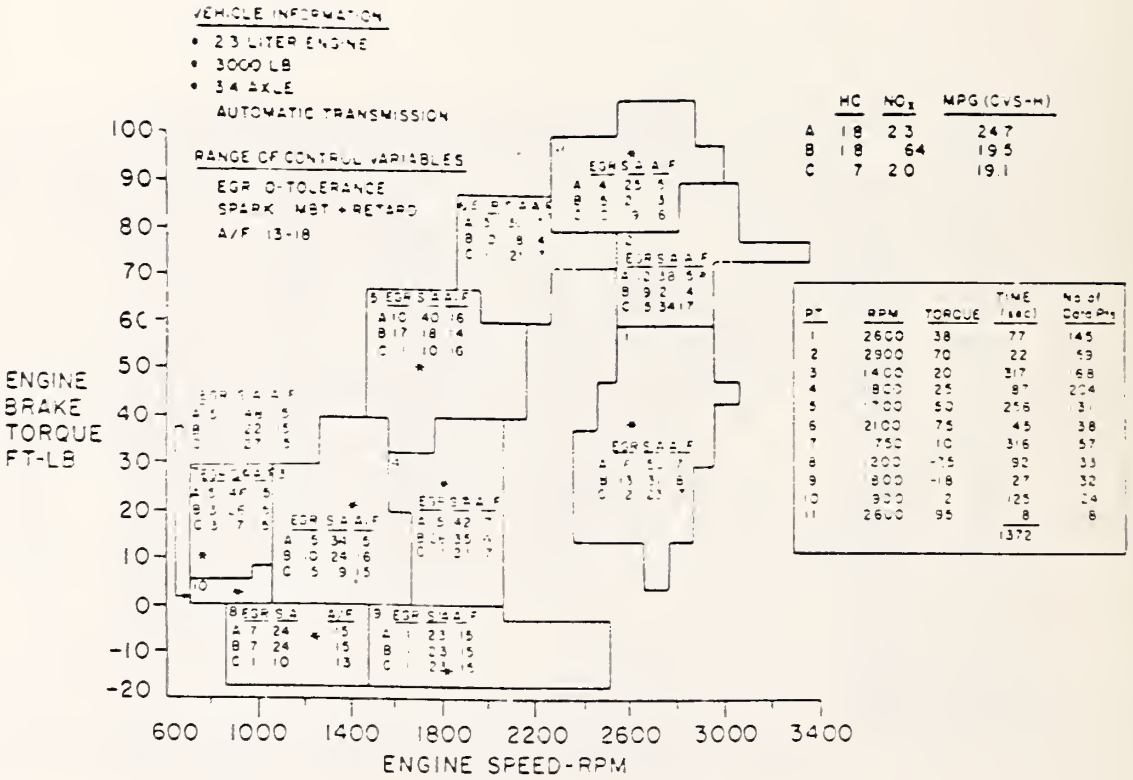
CLOSED THROTTLE

ROAD LOAD

FULL THROTTLE

Source: Reference 2.

FIGURE 2-23. TIME DISTRIBUTION MATRIX (SECONDS) FOR FEDERAL COMBINED URBAN-HIGHWAY TRIP SCHEDULE, EXCLUDING URBAN WARMUP



Source: Reference 3.

FIGURE 2-24. ENGINE CONTROL VARIABLES CORRESPONDING TO SELECTED OPTIMAL CALIBRATION SHOWN AT EACH TEST POINT FOR THE 2.3 LITER DATA BASE

steady-state it represents the "best" that can be accomplished independent of the dynamic errors associated with various engine controllers, and 3) it represents a specification requirement on the design and capability of any proposed engine control system.

The disadvantages in using this procedure are 1) because only steady-state data is employed, the treatment of emissions and fuel consumption during the cold-start and warm-up portion of the FTP must be excluded from the optimization process (typically 80 percent of the HC and CO emissions occur during the cold-start portion of the test); 2) because only steady-state data is employed the effects of A/F ratio and temperature variability on the dynamics of exhaust gas aftertreatment devices are ignored, and 3) the optimal control laws generated tend to ignore the degraded driveability associated with pushing the controls into regions of marginal combustion stability.

Nevertheless, this procedure has given direction to emission engineers in their attempt to optimize engine controls and has been used in the justification for electronic microprocessor-based controllers which have the capability, dynamically and computationally, of implementing the complex and interactive control strategies. Test results have shown that optimizing three key engine control variables (spark, EGR, A/F ratio) for a given hardware mechanization can yield an 8 percent improvement in fuel economy over conventional calibration techniques.

Dohner's[4] approach to the system-wide control problem is very different because it by-passes the processes of speed-load approximation to the FTP schedule and static dynamometer data gathering. Instead, he proposes a Transient System Optimization (TSO) procedure that is iterative in nature and uses data measured during the actual FTP test. The approach is to optimize the engine-vehicle system over the entire transient emission and fuel economy test schedule, not just at selected speed-load points.

Figure 2-25 depicts the experimental set-up and a block diagram of the iterative procedure. The set-up consists of the engine, transmission, catalytic converter, engine dynamometer, engine control computer, driver, driver's aid and data acquisition systems. The relationship among engine control variables, emissions, fuel consumption and driveability are represented by a system of state equations:[4]

$L = L\ (A/F,\ SA,\ EGR,\ t)$: fuel mass consumption rate

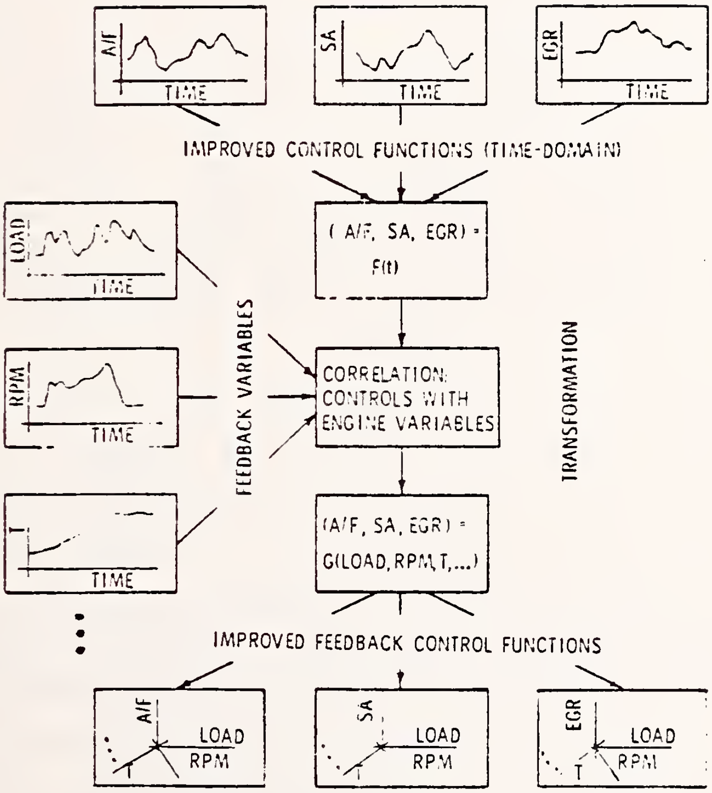
$$\left.\begin{array}{l} X_1 = f_1\ (A/F,\ SA,\ EGR,\ t) \\ X_2 = f_2\ (A/F,\ SA,\ EGR,\ t) \\ X_3 = f_3\ (A/F,\ SA,\ EGR,\ t) \\ X_1(0) = 0 \quad X_1(T) \leq HC^* \\ X_2(0) = 0 \quad X_2(T) \leq CO^* \\ X_3(0) = 0 \quad X_3(T) \leq NO_x^* \end{array}\right\}$$

: States are accumulated exhaust emissions, therefore at time T (end of test) the state variables must be less than or equal to emission constraints HC^*, CO^*, NO_x^*

$C(t) = C\ (A/F,\ SA,\ EGR,\ t)$: Driveability function

The optimal control solution, utilizing the Hamiltonian function, Lagrange multipliers and an iterative gradient procedure,[4] results in an open-loop time-variant correction function to the control laws imposed during the initial run.
This corrected control time-history is then correlated to the measured engine state parameters. These time-invariant controls are now programmed into the engine control computer for the subsequent test.

The advantages to such a procedure are 1) the iterative procedure will converge to the optimal solution for that particular hardware configuration; 2) the lack of convergence will indicate that a key engine state variable is not being measured; thus the procedure can specify the required inputs for the real-time engine control system; 3) it does take into consideration the dynamics of the entire FTP schedule including warm-up profiles and the transient response errors associated with the inability of given controllers (e.g. carburetors) to deliver the commanded value



Source: Reference 4.

FIGURE 2-25. SYNTHESIS OF THE IMPROVED FEEDBACK CONTROL FUNCTION

of the control variable, and 4) it verifies by its very nature that the control trajectory is physically realizable.

The primary disadvantage of the TSO procedure is that by its very nature it optimizes engine calibration subject to the limitations of the included control hardware. Therefore, it would be incapable of projecting the potential improvement if the characteristics of the controller were improved (e.g. going from a carburetor A/F ratio control system to an EFI-based A/F ratio control system). However, assuming the emissions engineer has chosen his hardware carefully, the TSO procedure will define the transfer function for the engine controller which will minimize fuel consumption. The results indicate that the number of required inputs to the control system, the complexity of the control laws generated, and the highly interactive nature of each emission control subsystem preclude any other choice but a microprocessor-based electronic engine control system. A microcomputer has the capability of implementating the optimal <u>open-loop</u> calibrations defined by both philosophies discussed here.

One last point is that none of the work described above has addressed two critical issues with respect to emission controls. The first is how to guarantee federal certification from within the constraints of manufacturing tolerances and engine-to-engine variability across a given production fleet. The second is how to guarantee emissions and fuel economy performance over the required 50,000 miles within the constraints of known engine/emission system degradation. Advances in electronic closed-loop feedback control via new sensor technology will be required before these two problems can be resolved.

Section 3.0 describes the present electronic and sensory technology available as defined by systems introduced by foreign and domestic manufacturers in 1977 and 1978.

3. STATUS OF PRESENTLY PRODUCED ELECTRONIC POWERTRAIN CONTROL SYSTEMS

3.1 GENERAL

Section 2 of this study discussed all primary engine/emission subsystems placing particular emphasis on the sensitivity of emissions and fuel consumption to the precision of control. In each case, it was discussed how electronic controls could be used to improve the inherent capability of the given mechanical hardware sybsystem. Some of the electronic control concepts outlined in Section 2 have been introduced into the domestic market. Although in many cases the control strategy is still quite crude, these systems offer an opportunity to judge the impact of electronic control systems to date. Table 3-1 outlines vehicle wide uses of electronics in today's automobiles, but the systems of interest here, are those that directly impact emission control and engine efficiency. The electronic control systems briefly reviewed here are the following;

1. Chrysler's Lean-Burn System
2. GM's MISAR System
3. Ford's EEC-I System
4. GM's Phase II Closed-Loop Carburetor/Catalyst System
5. Ford's ECU-A Feedback Carburetor/Catalyst System
6. Volve Lambda - Sound System

3.2 CHRYSLER'S LEAN-BURN SYSTEM

The Chrysler Lean-Burn system was first introduced on the 1976 400 CID engine. This system consisted entirely of analog circuitry designed with 741 op amps. Chrysler discovered that electronics could provide a substantially more accurate engine control system but it could not improve the fundamental problems of fuel economy and emissions unless more advanced spark and fuel control algorithms were developed. The lean-burn concept was to

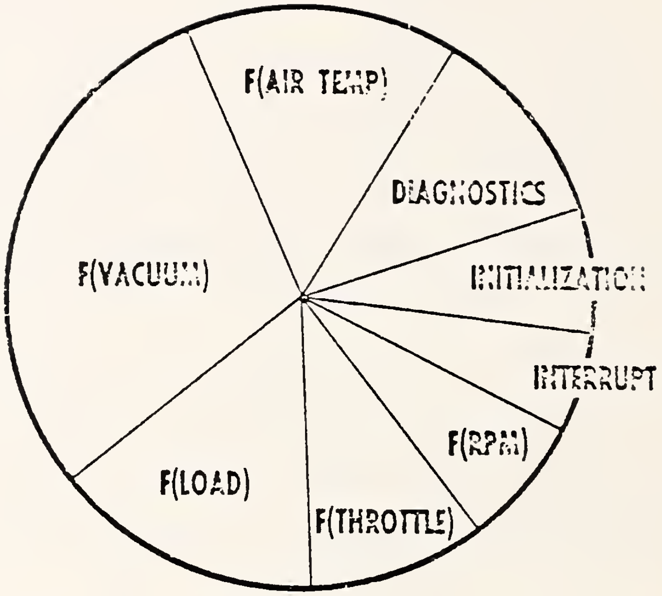
TABLE 3-1. ELECTRONIC PRODUCTS IN 1978 MODEL U.S. AUTOMOBILES

PRODUCT	IMPLEMENTATION	CAR MODEL
Tripmaster	Microprocessor	GM Cadillac Seville
Miles to Empty	L.S.I.	Ford Lincoln MK V
Fuel Injection	Analog	GM Cadillac Seville
Lean Burn (Spark)	Analog	Chrysler All V8's
Feedback Carburetor	Analog	Ford California Compacts
Closed Loop Carburetor	Analog	GM California L6 & V6
Closed Loop Spark Control	Logic + Analog	GM Buick Turbo Charged V6
Breakerless Ignition	Analog	All
Alternator Regulator	Analog	All
Electronic Spark Selector	Analog	GM Cadillac Seville
Multifunction Alarm	Logic + Analog	GM Buick & Cadillac
3 x 6 Valve Selector	Logic	Ford Trucks
Automatic Level Control	Logic + Analog	GM
Misar Spark Control	Microprocessor	GM Oldsmobile
EECI (Spark & E.G.R.)	Microprocessor	Ford Lincoln Versailles
Diesel Glow Plug Control	Analog + Logic	GM Oldsmobile 350 V8 Diesel
Gauge Alert	Analog	Chrysler
E.G.R. Delay	Analog	Chrysler
Backlight Delay	Analog	Chrysler & GM
Headlight Control	Analog	GM & Chrysler
Speed Control	Analog	Ford & GM
Anti-theft	Logic	GM
Tachometer	Analog	GM
Digital Clock	L.S.I.	All
Digital AM Radio	Logic	Ford
Search Tune Radio	Microprocessor	Chrysler

take advantage of the reduced emissions and fuel consumption associated with air/fuel ratios of 18 to 1. It was found that carburetors calibrated to this level required precise ignition timing that was not achievable with mechanical distributors. A system which could implement a complex algorithm and respond quickly to changing conditions was required. With the help of additional sensor inputs, the electronic module met this requirement. In anticipation of growing complexity and the integration of additional functions, Chrysler developed a microprocessor version of its Lean-burn module (ref. Figure 3-1). The system uses time since start, throttle position, rate of change of throttle position, air temperature, vacuum, and engine speed to compute desired spark advance. The computer is based on the standard RCA 1802 (8 bit) microprocessor and has 32 bytes of RAM and 1024 bytes of ROM to accomplish the control function. Section 3.8 documents the fuel economy gains achieved by using the Chrysler lean-burn system.

3.3 GM's MISAR SYSTEM

MISAR (Microprocessed Sensing and Automatic Regulation) is a microprocessor-based electronic spark control system ref. Figure 3-2). The microprocessor is believed to be a 10 bit Rockwell version. The inputs to the controller are engine speed (via a crankshaft magnetic pick-up sensor), intake manifold vacuum (for load indication), and atmospheric pressure. The details of the control strategy are not known, but the sensor inputs indicate that spark advance is a function of speed and load with compensation for altitude changes. General motors chose a microprocessor system because the control trajectories required could not be accomplished by mechanical distributors, the transient response of electronics is better and because of the repeatability, durability, long term accuracy of electronic ignition. The MISAR system represents an attempt by GM to gain experience with electronics and if successful, additional functions like EGR control and fuel control will be integrated. Section 3.8 documents the fuel economy gains achieved via the MISAR system.



$$F(SA)=F(RPM)+F(VAC)\times F(LOAD)+F(THROTTLE)\times F(AIR)+F(ON\ TIME)$$

Source: Reference 17.

FIGURE 3-1. CIRCLE CHART OF SOFTWARE REQUIREMENTS, AND SPARK ADVANCE EQUATION

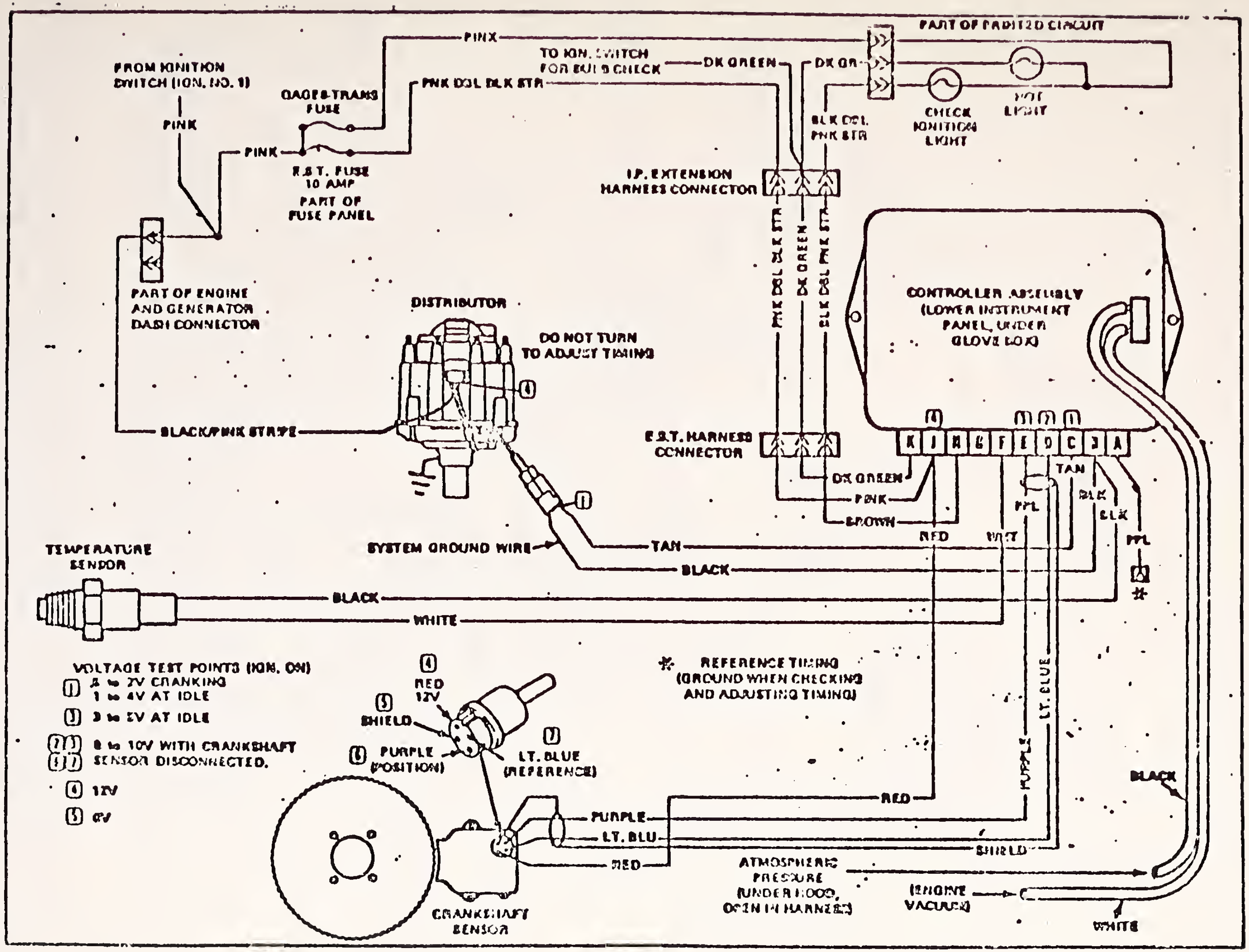
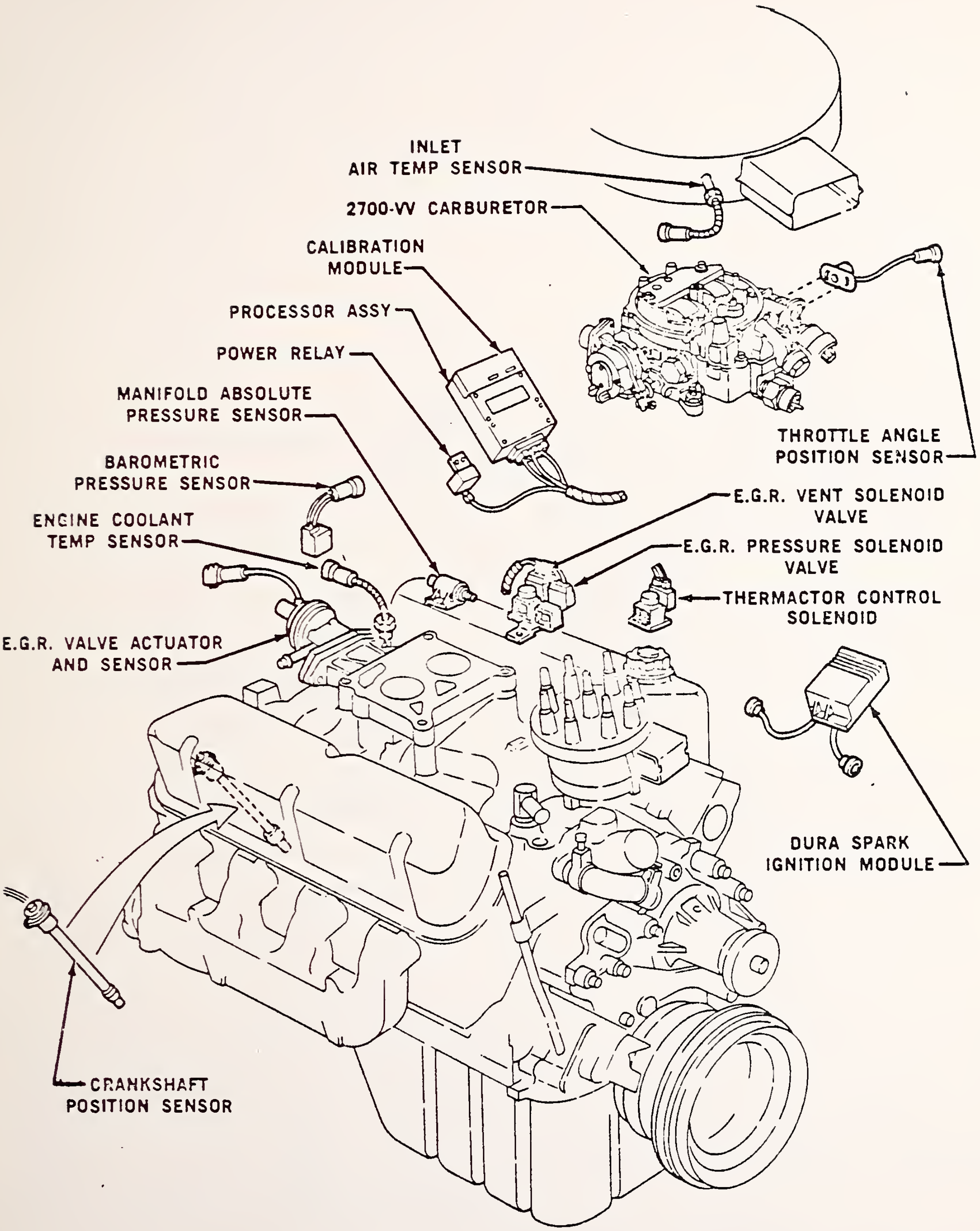


FIGURE 3-2. IGNITION SYSTEM WIRING, MISAR SYSTEM-GM

3.4 FORD EEC-I SYSTEM

The Ford EEC-I system (a microprocessor based electronic engine control system) was introduced on the 1978 Lincoln Versailles model equipped with the 302 CID engine. This new system was the first in the industry to simultaneously coordinate two primary engine operations: spark advance and exhaust gas recirculation (EGR) rates. Figure 3-3 depicts all of the components that make up the EEC system. The processor assembly senses the following inputs: crankshaft position (in order to compute engine RPM and to initiate proper ignition timing), EGR valve position, barometric pressure (altitude correction), manifold absolute pressure (load indication), engine coolant temperature (cold engine/over temperature compensation), and throttle angle position (for mode control: idle, decel, part throttle, wide open throttle). The processor assembly consists of a general purpose 12 bit microprocessor (Toshiba design), an 8 bit analog-to-digital converter, 1024 words of ROM(read-only-memory), 256 words of RAM (random access memory) and special purpose integrated electronic circuits to output control signals to three actuator subsystems. The microprocessor assembly is designed to be a general purpose electronic EGR, spark and thermactor air controller. Figure 3-4 shows that the specific calibration parameters, which are inputs to the general control software, are stored in a plub-compatible calibration assembly. It is this calibration assembly and the parameters it contains that determines whether the electronic system is set up to control a 302 CID, 351 CID or a 400 CID engine. The combination of general control software and calibration parameters defines the engine control strategy, the outputs of which determine the desired state of the thermactor air control solenoids, the EGR valve actuator control solenoids and the Dura spark ignition module.

The spark advance control is open-loop and the spark advance set-point is computed by the microprocessor. In the closed throttle mode, spark advance is a function of engine speed and coolant temperature and in the wide open throttle mode, spark



Source: Reference 5.

FIGURE 3-3. 1978 EEC SYSTEM INSTALLATION

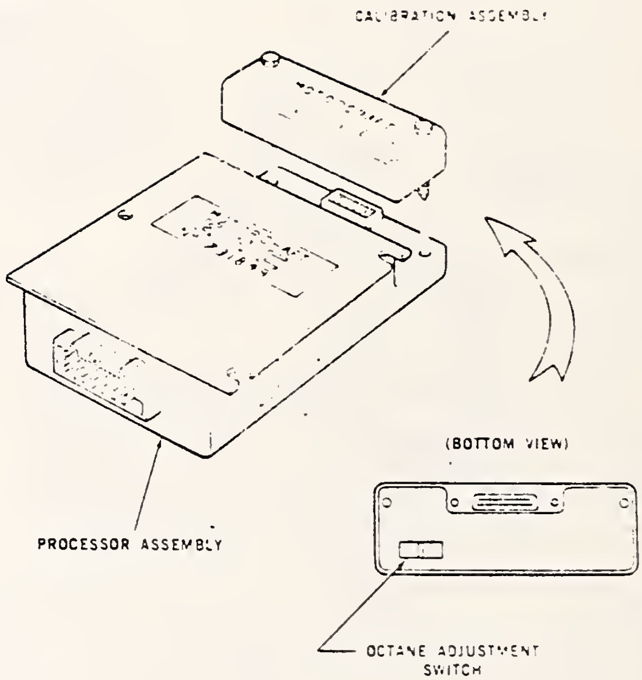


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FIGURE 3-4. ELECTRONIC CONTROL ASSEMBLY WITH CALIBRATION MODULE BREAK-AWAY

advance is a function of engine speed and coolant temperature and in the wide open throttle mode, spark advance is a function of engine speed, barometric pressure and inlet air temperature. In the part throttle mode, a spark advance look-up table exists with spark advance as a function of engine speed and manifold absolute pressure. The exact value of spark advance is determined by the "computer" by first performing a two dimensional linear interpolation between points in the table, then modifying (by addition or multiplication) this value by functions of coolant temperature, EGR actual precent flow, and inlet air temperature. This value of spark advance is placed into a hardware register inside the special purpose output circuit mentioned previously. This register is compared to the value in another register which continually changes with changing crankshaft position. When the two registers are equal, the ignition module receives a command to "fire." There is no attempt to close the loop on spark advance since there is presently no sensor to determine the value of "absolute" spark advance which has actually taken place. The distributor performs only the function of transmitting the high voltage from the coil to the appropriate spark plug since it has no provisions for centrifugal or vacuum advance mechanisms.

Thermactor air control also takes place open-loop and is done by the EEC system in order to optimize the catalyst warm-up profile. In both closed throttle and part throttle modes, thermactor air control is a function of inlet air temperature. If inlet air temperature indicates a cold engine and thus a cold catalyst, the thermactor air is "dumped" to the atmosphere. When the system is up-to-temperature, the thermactor air control solenoid is energized by the EEC module and thermactor air is injected into the cylinder head exhaust ports. This supplies sufficient free oxygen to allow the COC (conventional oxidation catalyst) to oxidize the HC and CO species in the exhaust stream. In wide open throttle, thermactor air is dumped to the atmosphere.

Since the TWC (three-way catalyst) is presently not used with the EEC system, EGR control becomes critical with respect to NO_x

abatement. Figure 3-5 shows the typical EGR system used with EEC. The EEC/EGR system represents an industry breakthrough in emission engine control for the following reasons:

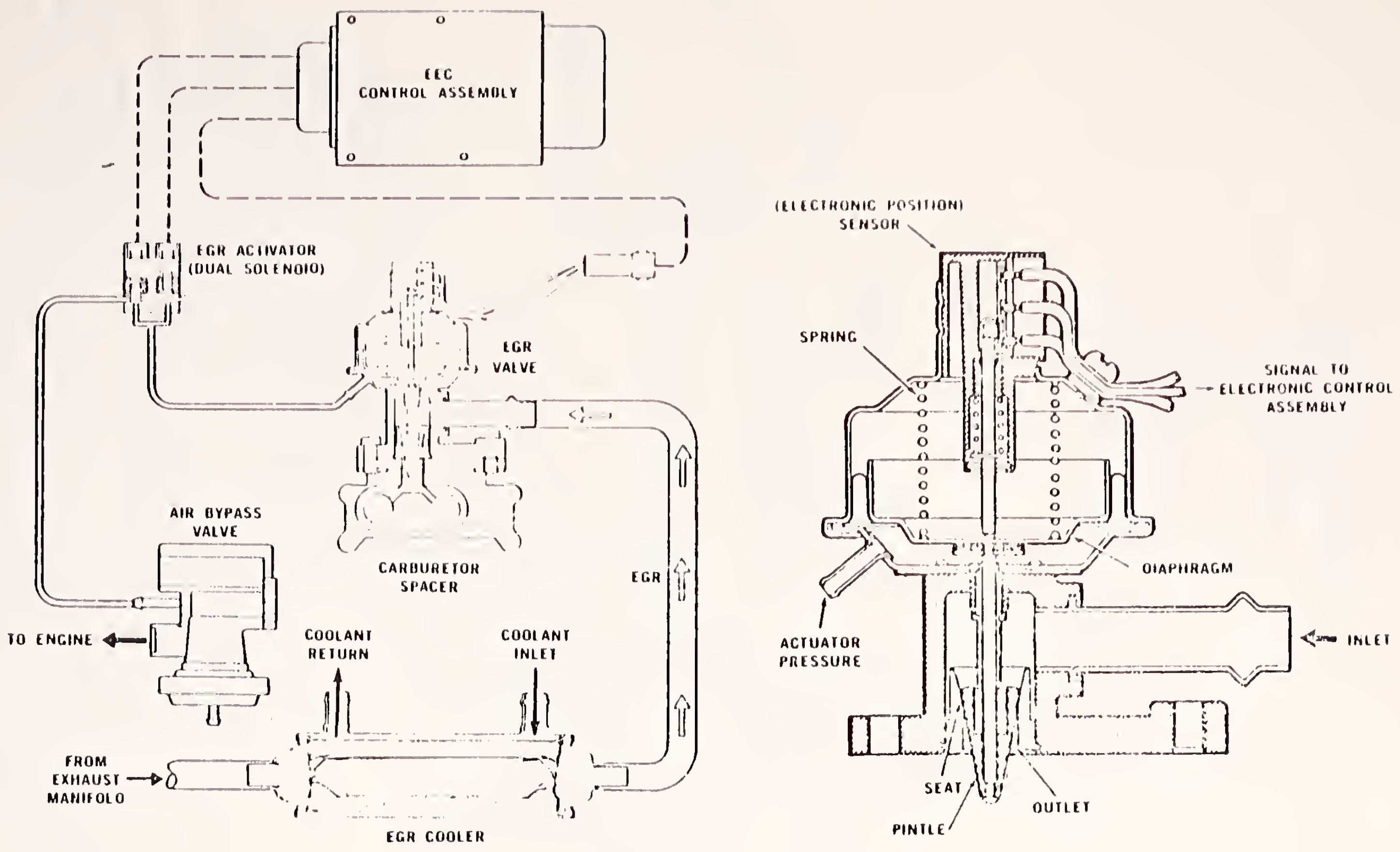
1. The EGR valve is a sonic flow valve, therefore, EGR Mass flow through it is independent of the depression or pressure fluctuations in the intake manifold.

2. The EGR cooler is used to cool the EGR gases in order to increase the density of exhaust gases actually recirculated.

3. The EGR valve is equipped with a valve position sensor allowing for closed-loop control to be used. Within dynamic response capability of the electronics and the valve actuator, the EEC corrects valve position approximately 10 times a second. This continuous monitoring of pintle position allows precise control of EGR flow both dynamically and as the valve wears with age, resulting in improved fuel economy and vehicle driveability.

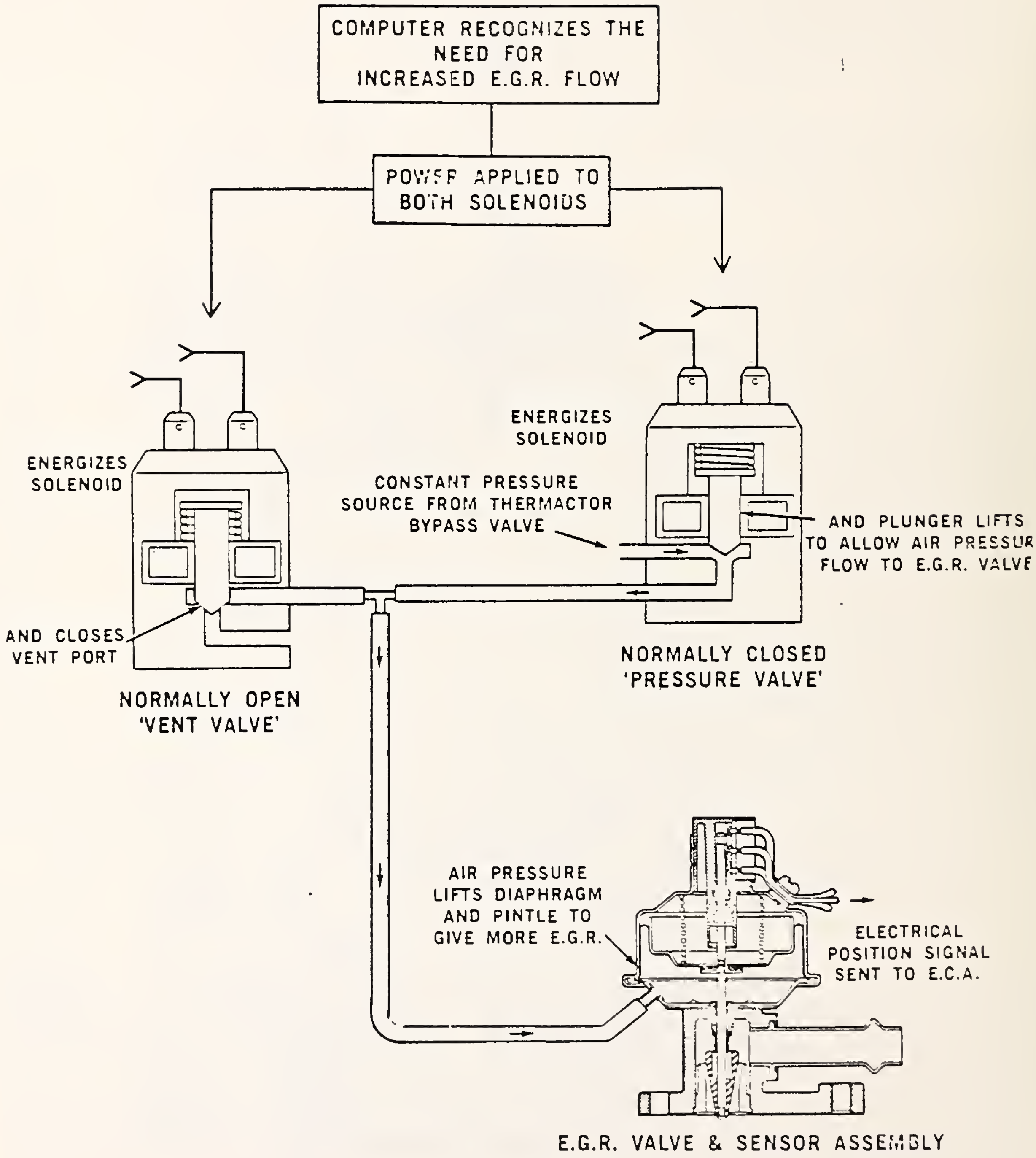
4. Since both EGR and Spark are controlled by the same computer, spark advance in part throttle is a function of actual EGR percent flow. This spark advance modulation based on actual EGR valve position is an emissions compensation for the difference between the strategy desired EGR percent and the actual EGR percent. This interactive control allows for emission compensation through one engine control variable if the performance of another control variable begins to degrade.

In the closed-throttle and wide-open-throttle modes, the EGR valve is commanded closed. In part-throttle, the desired EGR percent mass flow is determined from a table of EGR values versus engine speed and intake manifold pressure. This value is then modulated by functions of engine coolant temperature, barometric pressure and inlet air temperature. Figure 3-6 shows some of the details of the EGR valve actuation system. The desired EGR valve position, as defined by the above software stragegy, is accomplished



Source: Reference 5.

FIGURE 3-5. 1978 TYPICAL EGR SYSTEM USED WITH EEC AND TYPICAL EEC SYSTEM--EGR VALVE



Source: Reference 5.

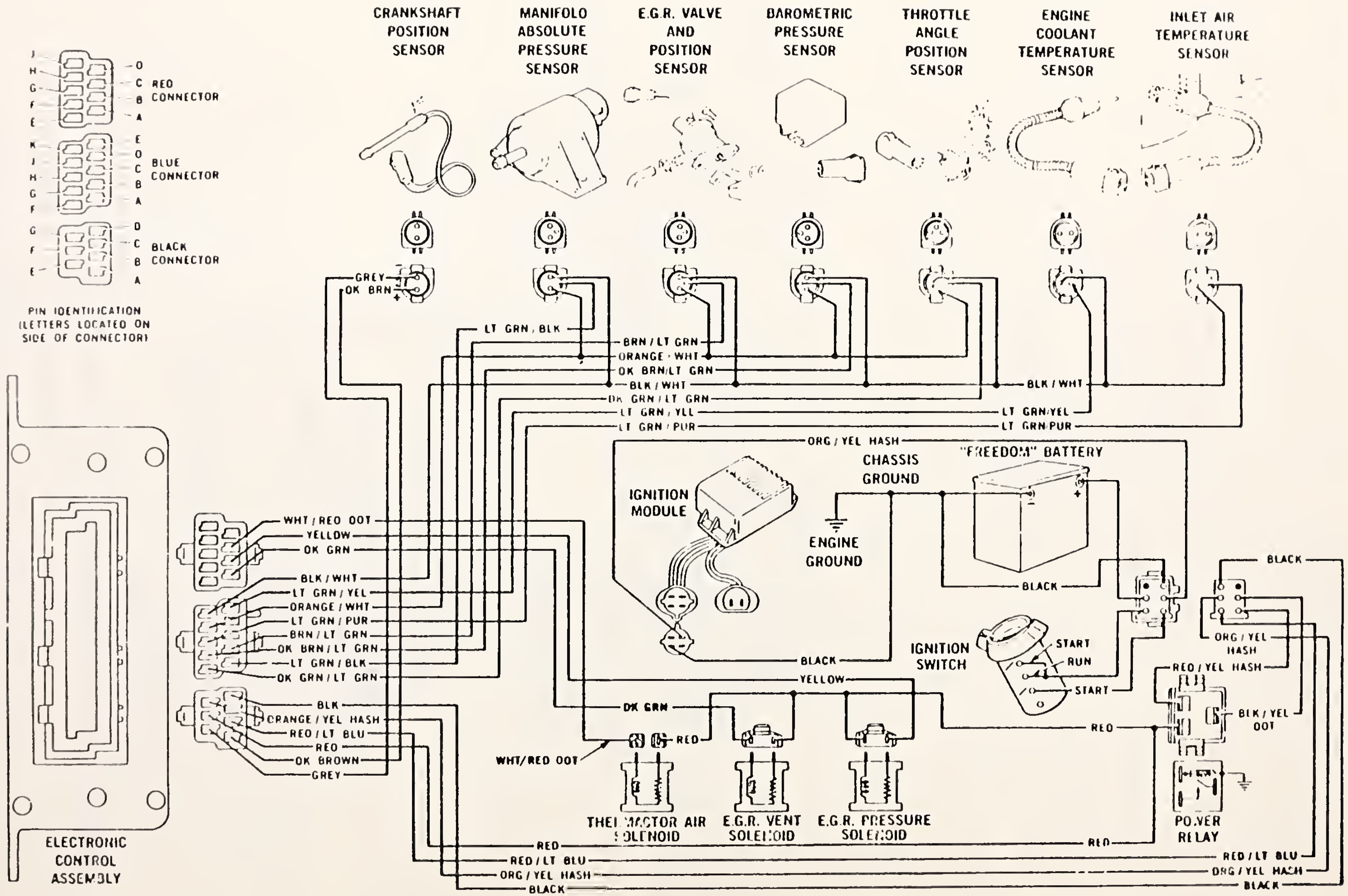
FIGURE 3-6. "INCREASE EGR"--SYSTEM OPERATION

via this actuator subsystem. The EGR valve pintel is moved by an air pressure source acting on the spring loaded diaphragm. This air pressure source is modulated by electronically switching two electric solenoids. One solenoid allows atmospheric pressure into the line (closing the valve) and the other allows pressurized air from the thermactor air pump into the line (opening the valve). The EEC module receives a feedback signal from the EGR valve potentiometer and compares this value to the desired setpoint. The error that may exist is used to determine the pulse-width modulated voltage signal that is sent to each solenoid in order to position the valve to the desired setpoint. This EGR system does not, however, eliminate the problems associated with single point entry as discussed in Section 2.2.

Figure 3-7 shows the interconnections of the various EEC components. It is apparent that Ford Motor Company believes that the complex control algorithms required to optimize spark advance and EGR rates and to make best use of the interactive aspects of these two engine/emission variables, a microprocessor based electronic control system is required, especially in terms of its dynamic response and computational powers. Ford has indicated that advance versions of the EEC system will be introduced in future years in order to implement fuel metering control on carburetors, throttle body injection systems and the PROCO stratified charge engine. The impact of this first version, EEC-I, on fuel economy is discussed in Section 3.8.

3.5 GM'S PHASE II CLOSED-LOOP CARBURETOR/CATALYST SYSTEM

General Motors introduced (California only) its Phase II closed-loop carburetor/catalyst system[18] on two 1978 engine families (in California only). One is the 2.5 liter L-4 engine and the other is a 3.8 liter V-6 engine. Both systems include closed-loop carburetors and three-way catalysts (TWC) to achieve simultaneous control of NO_x, HC and CO emissions. Figures 3-8 and 3-9 show the two Phase II control systems as they presently exist in production. The motivation for feedback control of A/F ratio is discussed in detail in Sections 2.4 and 2.5 of this report. The



Source: Reference 5.

FIGURE 3-7. 1978 EEC LINCOLN VERSAILLES WIRING DIAGRAM

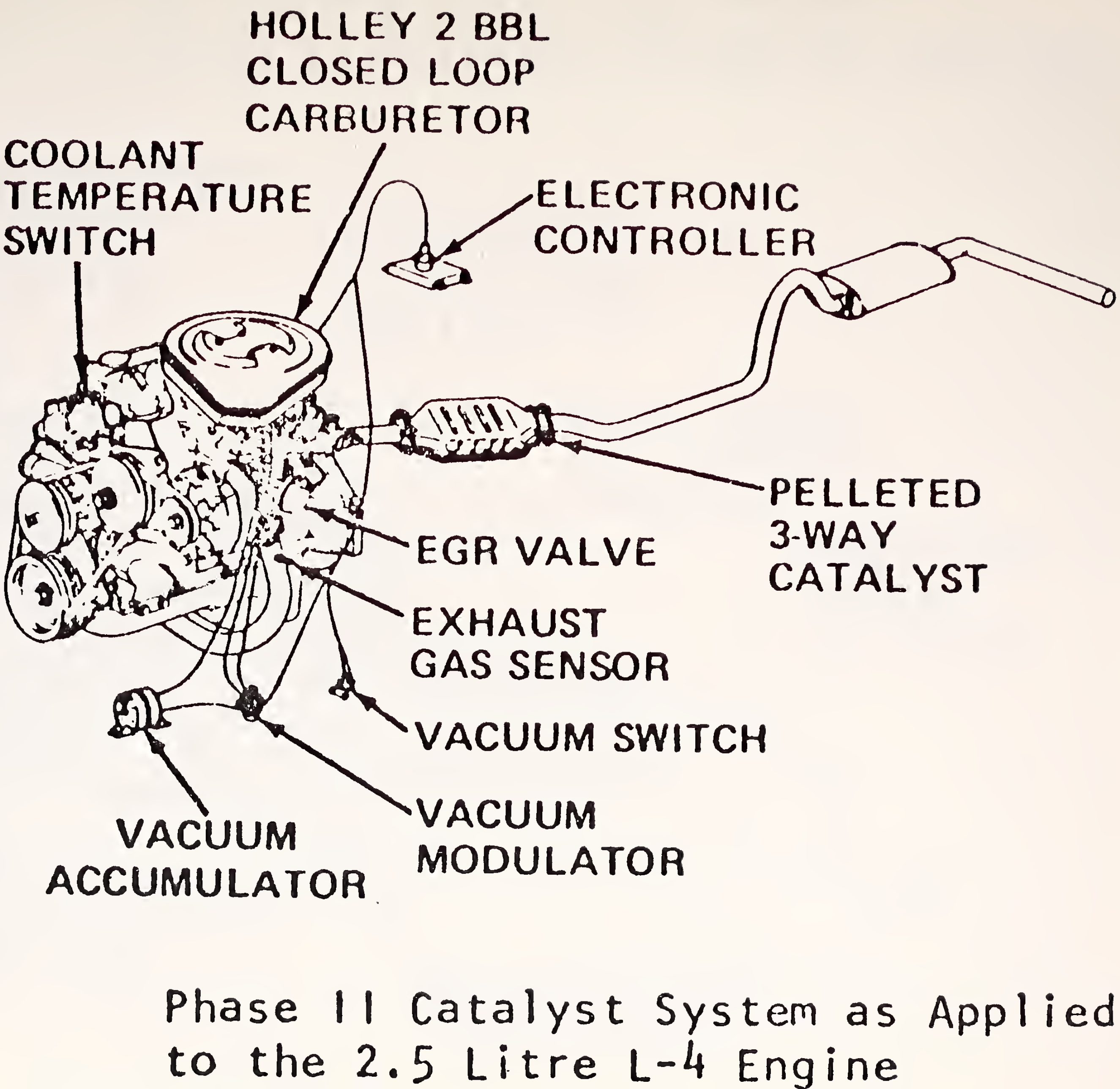


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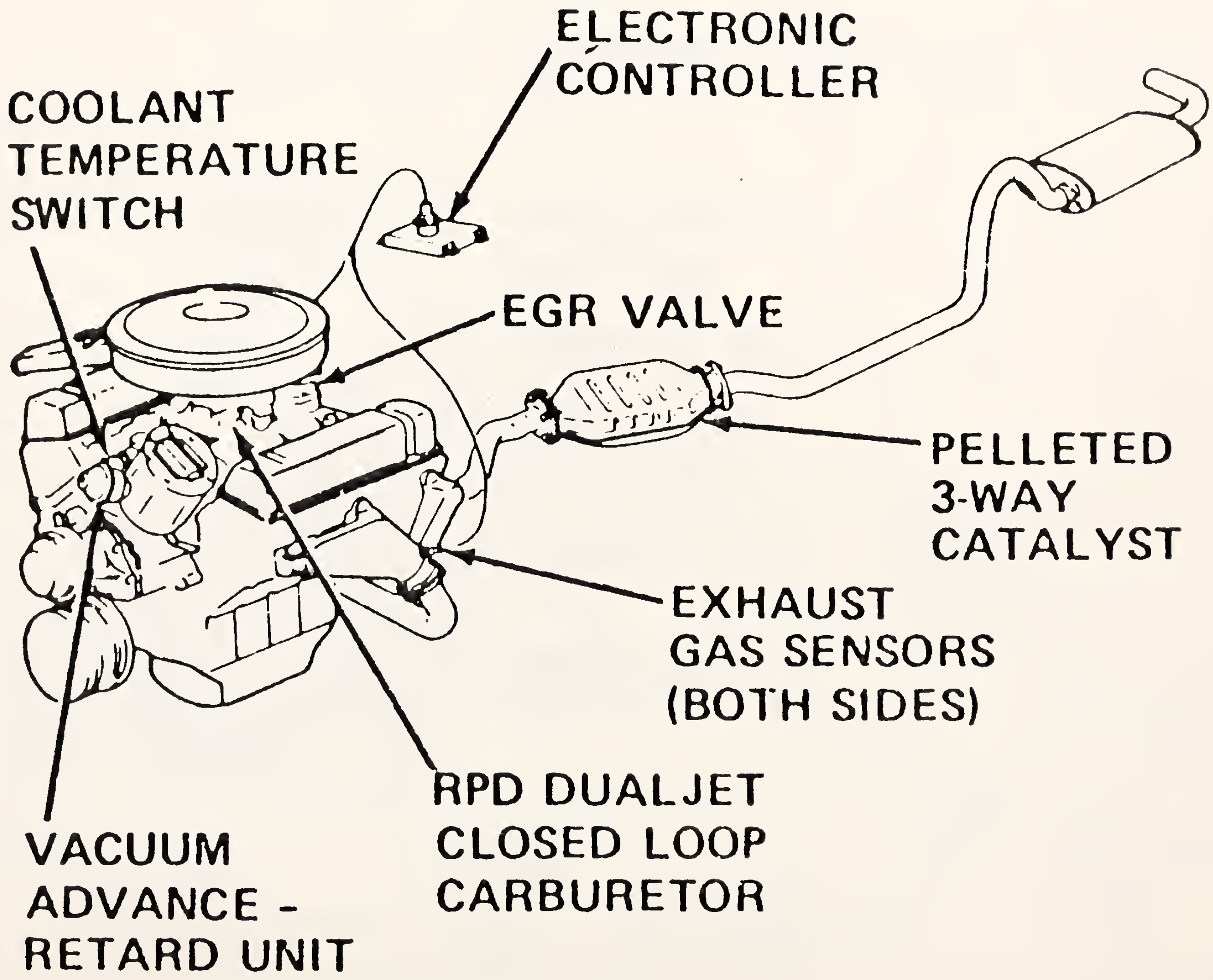
FIGURE 3-8. CLOSED LOOP DUAL CATALYST SYSTEM



Phase II Catalyst System as Applied to the 3.8 Litre V-6 Engine

Source: Reference 18.

FIGURE 3-9. CLOSED LOOP THREE-WAY CATALYST SYSTEM

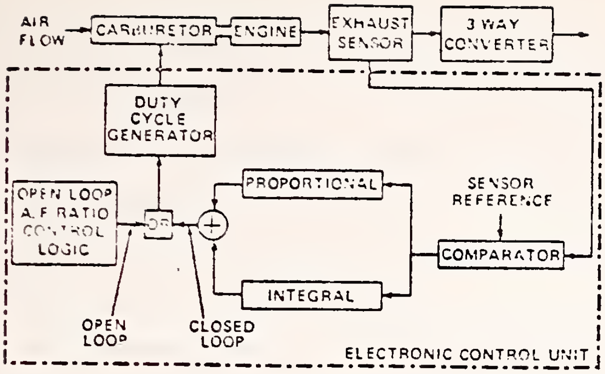
Phase II system utilizes the fact that the characteristic maximum conversion efficiencies of a three-way catalyst occur near the stoichiometric A/F ratio and that the non-linear switching characteristics of the zirconium dioxide sensor also occur near the stoichiometric A/F region (ref. Figures 2-18 and 2-20). Therefore, the interesting aspect of this particular fuel control system is the means by which the A/F ratio correction-limit-cycle (ref. Figure 2-20) is imposed on the feedforward fuel metering signal. On the 2.5 liter L-4 engine, this is accomplished using a Holley staged two barrel carburetor, and on the 3.8 liter V-6 engine, a Rochester Products Dualjet carburetor is utilized (ref. Figure 3-8 and 3-9). The variation in A/F ratio is accomplished differently in each carburetor. The Holley system uses an electronically modulated vacuum source where the vacuum supplied to the idle bleed circuit or the vacuum actuated main metering rod determines the A/F ratio delivered by each circuit. The Dualjet carburetor design eliminates the vacuum interface by inserting a solenoid directly in the float bowl. The solenoid, which is electronically activated, drives a pair of stepped metering rods in the main metering jets at the same time that it drives a stepped rod in an air bleed orifice in the idle circuit. In both carburetor designs, the controls for the idle and part throttle circuits are phased so that a lean command produces a leaner A/F ratio and a rich command results in a richer A/F ratio from both circuits. An attempt is also made to insure that the dynamic flow curve (A/F ratio vs air flow) is relatively flat. This means that a given command signal from the controller should yield the same A/F ratio on the idle circuit and part throttle circuit, thus minimizing the A/F disturbances due to transients that the closed-loop system has to correct.

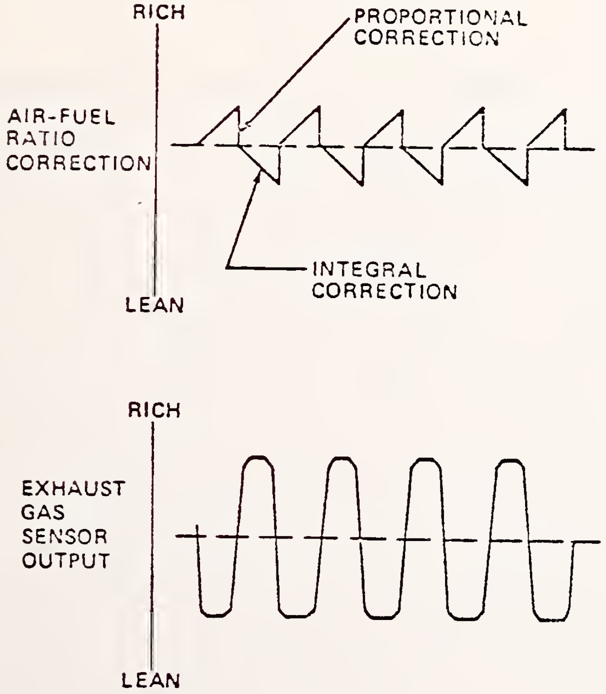
It should also be noted that on the 3.8 liter V-6 engine, the intake manifold is split from side to side so one bore of the carburetor feeds the left bank of cylinders while the other bore feeds the right bank of cylinders. Therefore, to minimize sensor warm-up times and system transport delay times, and to insure that

the TWC sees a true average A/F ratio of the total exhaust flow, a sensor is mounted in each exhaust manifold of the V-6 engine. The ECU (electronic control unit) performs on "AND" control function on each sensor output insuring no change in limit-cycle direction until both sensors have switched.

The ECU also performs special compensation functions when the feedback sensor is too cold, when the engine coolant temperature is below 150°F and when the throttle plates are at wide-open-throttle. The ability to perform multifunction compensation with multiple inputs is a significant advantage of electronic control logic. The ECU is believed to be a special purpose control device using a few bipolar integrated circuits and supporting discrete components. As the fuel control function becomes integrated with other electronic systems (ESS or MISAR), it is believed that the more cost-effective general purpose microprocessor based system will be introduced across all engine families.

As outlined in Section 2.5, changes in the A/F mixture generated by carburetor error, distribution problems in the engine/intake manifold system, and transient effects due to flow variations through the engine can be observed by the sensor only after the system transport delay time which is known to be excessive in carburetor based feedback systems. Figure 3-10 shows the strategy or control law of the Phase II ECU and how it attempts to improve the frequency response of the feedback carburetor concept by introducing both proportional and integral control. The amount of proportional correction is computed from the integral gain and the amount of time since the sensor last switched voltage state. Also, the integral gain while driving the A/F ratio rich, can be different from the integral gain while driving the A/F ratio lean. This function offers the capability of biasing the mean A/F ratio slightly lean or slightly rich of stoichiometry and it is typically introduced as a function of engine load or intake manifold vacuum. Under light load conditions, NO_x formation rates are low and therefore slightly lean A/F ratios will improve HC and CO conversion efficiencies. Alternatively, under heavy loads, NO_x formation





Source: Reference 18.

FIGURE 3-10. FUNCTIONAL SCHEMATIC OF THE CLOSED-LOOP SYSTEM, AND PROPORTIONAL AND INTEGRAL CORRECTIONS MADE BY THE ELECTRONIC CONTROL UNIT

rates are high and slightly rich A/F ratios will improve NO_x conversion efficiencies. All of the above mentioned "fine" adjustment control laws, however, will have a favcrable impact only if the A/F ratio delivered by the carburetor/intake manifold system to each cylinder remains relatively flat during all engine transients occurring throughout the FTP test. It is a well known fact that intake manifold dynamics represent the significant obstacle in accomplishing this open-loop control requirement.

Regardless of the limitations of feedback carburetor systems in general, the improved A/F ratio control that has been accomplished with the Phase II system, has resulted in improved catalyst conversion efficiencies, less conservative EGR and spark advance calibrations, and a 14 percent improvement in fuel economy over conventionally equipped cars. These results are documented in Section 3.8.

3.6 FORD'S ECU-A FEEDBACK CARBURETOR/CATALYST SYSTEM

Ford Motor Company introduced on the 1978 2.3 liter L-4 engine, the ECU-A (electronic control unit) feedback carburetor/catalyst system. This system is available only on California Pinto/Bobcat models. The Ford system uses a staged Holley Webber 2-bbl carburetor equipped for feedback control. The fuel modulation technique, actuator subsystem, ECU electronic technology and control logic are all very similar to the GM 2.5 liter L-4 engine system (Phase II). The primary difference is that the Ford ECU does not use the proportional correction scheme but, instead, implements the simpler integral-limit-cycle only. Ford also claims that the sensor maintenance schedule has been extended from 15,000 to 50,000 miles. It is not believed that this extended durability is due to improved sensor design, but instead is due to the fact that with simple integral control, the closed-loop system is less sensitive to sensor response-time degradation with mileage and, therefore, can tolerate degraded sensor performance over a longer period. The results obtained to date with the ECU-A system are documented in Section 3.8.

3.7 VOLVO LAMBDA-SOND SYSTEM

The Volvo Lambda-Sond System was introduced on the 2.1 liter L-4 engine for the 1977 California market. It represents the most sophisticated and comprehensive engine/emission control system to date. The system is composed of the Bosch K-jetronic continuous fuel injection system, the three-way catalyst, and a closed-loop fuel control system. The advantages of combining these three systems in this manner is emphasized throughout Sections 2.3 and 2.5 of this report and there is no need to repeat the details here. Figure 2-10 details the various components that make up the Volvo system. As pointed out in Sections 2.3 and 2.5, the combination of an intake port fuel injection system (whether mechanical or electronic) and a closed-loop fuel correction represents an optimal weighting or mix of bandwidths (frequency response characteristics) of each particular system. In other words, a feedback fuel control system is best utilized by a fuel injection system and the performance of a fuel injection system is greatly enhanced by a feedback fuel control system. Volvo has implemented this concept with great success. The Lambda-Sond system, as applied to both 3000 lb and 3500 lb inertia weight vehicles, has come very close to meeting the research goal of .41HC/3.4CO/.4NO_x with a 12 percent increase in fuel economy. Figure 3-11 shows the performance of this system both open-loop and closed-loop over the worst case transient conditions of the FTP test. This precise fuel control system has allowed for the elimination of traditional emission control systems such as EGR, air pump, and spark retard which, no doubt, accounts for the improved fuel economy. The zirconium dioxide sensor must be replaced at 15,000 miles primarily because the degradation in sensor response (time constant) represents a significant percentage of total system transport lag but this penalty is not considered restrictive. The more interesting aspect of this system will be the attempt to apply it to V-6 and V-8 engines. The results to date are documented in Section 3.8.

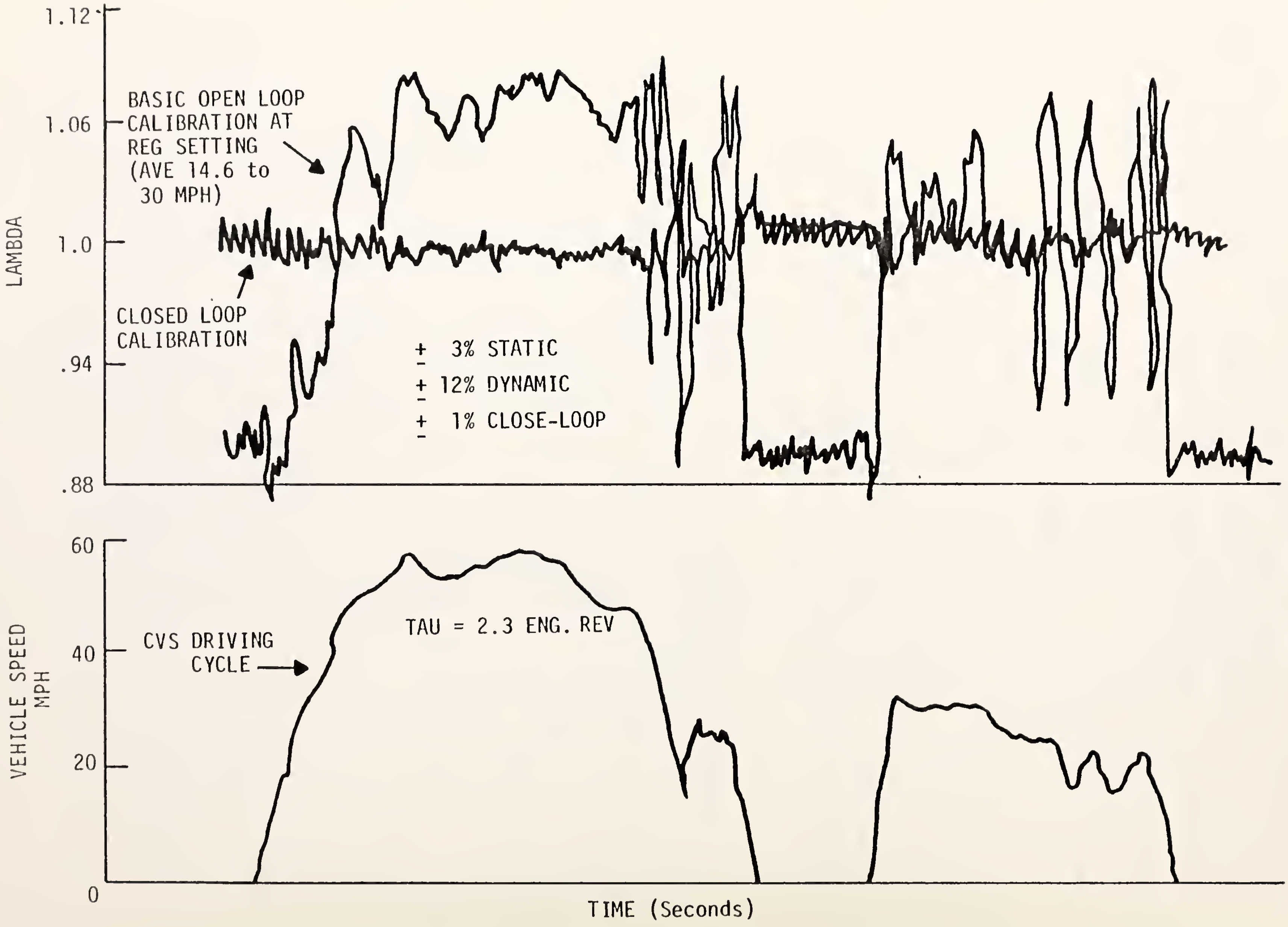


FIGURE 3-11. H/S 505-OPEN/CLOSED LOOP COMPARISON VOLVO LAMBDA-SOND, 3500 LB./11.2 HP

3.8 THE IMPACT OF ELECTRONIC CONTROL SYSTEMS TO DATE

Tables 3-2 and 3-3 document the fuel economy gains that are a result of the introduction of the electronic engine control systems described in Sections 3.2 to 3.7. The actual improvements are from 5 to 13 percent over the conventionally equipped baseline engines. Note that some of the vehicle/engine classes that showed an improvement, were also calibrated to stricter emission standards, indicating that slightly higher MPG improvements were possible. Also note that most of the electronic systems which exist today, optimize the control of a single variable (spark or A/F ratio) and the gains achieved independently may not be additive when systems are combined. Tables 3-2 and 3-3 can therefore only indicate trends and potential improvements via more precise control of engine parameters. Throughout this entire document, one point has been emphasized, that the engine/emission control system is a highly interactive one and that improving the precision of control of one engine variable inevitably leads to changes in the calibration of other variables, resulting in a multiplication effect in fuel economy gains.

As Tables 3-1 and 3-2 indicate, the initial introduction of electronic controls to three 4-cylinder engines and three V-8 engines with single variable control of spark, EGR or A/F ratio has caused a 1-13% improvement in fuel economy. Also note, that some of the vehicle/engine classes that showed an improvement were also calibrated to stricter emission standards, indicating that slightly higher MPG improvements were possible. In the comparison of Tables 3-1 and 3-2, the smaller vehicles and smaller engines showed a slightly better improvement figure indicating perhaps that throttling losses (which effect breathing efficiency) of the larger engines represent a barrier to fuel economy improvements.

TABLE 3-2. REFERENCE BASELINE* PRIOR TO INTRODUCTION OF ELECTRONIC CONTROLS

Source	MODEL	DISP IN^3	FEEDFORWARD FUEL CONTROL	COMP RATIO	INERTIA WT LBS	TRANS	AXLE RATIO	EMISSION STDS CALIB EMISSION CONTROL SYSTEM	CITY MPG	HIGHWAY MPG	COMBINED MPG
	FOUR CYLINDER ENGINES										
1977 CALIF. 7E2-2.3-C-36	FORD PINTO	140	2bbl CARB	9.0	2750	M4	2.73	1977 Calif. Stds. AIR/CAT/EGR/CAN	22	34	26
SAE PUB 770295	VOLVO SEDAN	130	FUEL INJECTED INTAKE PORT	8.5	3500	A3	3.91	1976 Calif. Stds. AIR/CAT/EGR	17	23	19
SAE PUB 780205	GMC Pontiac SUNBIRD	151	2bbl CARB	8.2	3000	A3	2.73	1977 Calif. Stds. /CAT/EGR/CAN	20	27	23
	EIGHT CYLINDER ENGINES										
1977 49S 9069	CHRYSLER Plymouth	400	4bbl CARB	8.2	4500	A3	2.45	1977 49S Stds. AIR/CAT/ /CAN	11	20	14
1977 Calif. 701-302-C-36	FORD Granada	302	2bbl CARB	8.4	4000	A3	2.47	1977 Calif. Stds. AIR/CAT/EGR/CAN	14	20	16
1977 49S 7341F4	CMC TORONADO	403	4bbl CARB	7.9	5000	A3	2.73	1977 49S Stds. /CAT/EGR/CAN	13	18	15

*Engine/Weight classes are representative of a cross-section of the automotive market and represent configurations that reflect electronic control applications to date.

TABLE 3.3. INTRODUCTION OF BASIC ELECTRONIC ENGINE CONTROLS ON LIMITED PRODUCTION TEST FLEETS

MODEL	DISP IN^3	FEEDFORWARD FUEL CONTROLLER	COMP RATIO	INERTIA WT LBS	TRANS	AXLE RATIO	EMISSION STANDARDS EMISSION CONTROL SYSTEM	CITY MPG	HIGHWAY MPG	COMB MPG	% IMPROVEMENT
FOUR CYLINDER ENGINES											
							1978 Calif. Standards				
FORD PINTO CALIF. ONLY	140	2 bbl CARB FEEDBACK	9.0	2750	M4	2.73	AIR/TWC/EGR/CAN Electronic Feedback Carburetor ECU-A	25	34	29	12%
							1977 Calif. Standards				
VOLVO SEDAN CALIF. ONLY	130	FUEL INJECTED INTAKE PORT	8.5	3500	A3	3.91	AIR/TWC/EGR/CAN Electronic Feedback A/F Ratio Control	18	26	21	12%
							1978 Calif. Standards				
GMC Pontiac Sunbird	150	2bbl CARB	8.2	3000	A3	2.73	/CAT/EGR/CAN EFC Feedback Carburetor	23	31	26	13%
EIGHT CYLINDER ENGINES											
							1978 49S Standards				
CHRYSLER CORDOBA	400	4bbl CARB	8.2	4500	A3	2.45	AIR/CAT/EGR/CAN Electronic Spark Control (Lean-Burn)	12	20	15	1%
							1978 49S Standards				
FORD VERSAILLES (Small Volume)	302	2bbl VV CARB	8.4	4000	A3	2.50	AIR/CAT/EGR/CAN EEC-I Spark and EGR Electronically Controlled	15	21	17	6%
							1978 49S Standards				
GMC TORONADO	403	4bbl CARB	7.9	5000	A3	2.73	CAT/EGR/CAN MISAR Electronic Spark Control	13	19	16	5%

4. SURVEY OF FUEL ECONOMY POTENTIAL IN THE 1980-1990 TIME FRAME ASSOCIATED WITH ELECTRONIC ENGINE CONTROLS

A survey of the fuel economy potential associated with electronic engine controls[19] indicates an increasing use of on-board electronics for engine control and for the implementation of engine calibrations. Table 4-1 summarizes the findings of the referenced survey. It shows that even though some introductory electronic modules were composed of analog circuitry (Ford's ECU-A Feedback Carburetor controller and Chrysler's LEAN BURN spark advance controller), they were primarily single function or single variable controllers. Future multifunctions or multivariable requirements will necessitate digital microprocessor control techniques. The advantages over analog circuitry lie in the microprocessor's ability for accuracy, repeatability and for the complex or shared logic applications. In addition it has the ability to follow sophisticated optimal control trajectories with excellent dynamic response and to accommodate rapid changes in engine calibrations late in the certification cycle. Electronic control of engines continues to be a versatile tool for optimizing conventional mechanical control systems. The basic parts of such an engine control system are:

1. Sensors for measuring "key" engine state variables
2. Actuators for initiating control over control variables
3. The electronic control system hardware (microcomputer)
4. The Control Strategy and Calibration Program (software)

the flexibility of this type of electronic control system permits easy comparison of several engine calibrations allowing for quick fuel economy and emission trade-offs to be made and giving deeper insight into the interaction of each control parameter.

The time schedule in Reference 19 given for the introduction of microprocessor-based electronic control systems for each manufacturer is outlined in Table 4-1. Figure 4-1 presents the total integrated engine/powertrain control system that is anticipated

TABLE 4-1. ELECTRONIC ENGINE CONTROL SYSTEM IMPROVEMENTS BY DOMESTIC MANUFACTURERS

	ENGINE TYPE	1977	1978	1979	1980	1981	1982-1990
CHRYSLER	4 cyl		Lean-Burn on 1.7ℓ	Turbocharger on 1.7ℓ			
	V-8	Lean Burn Selected V-8's	Lean-Burn on all V-8's	Microprocessor-based Lean-Burn on all V-8's EFM on selected V-8's			
GENERAL MOTORS	4 cyl		Feedback carb w/TWC cat - Calif 151 CID			Microprocessor based spark, EGR and closed-loop fuel control	
	IL-6 V-6		Buick Turbo 231 CID with feedback knock control	Feedback carb w/TWC CAT on all 495			
	V-8		MISAR-Toronado ESS (Electronic spark selection) Seville	Microprocessor based spark and EGR control on all V-8 engines			
FORD	4 cyl	Dura Spark ignition systems All engines	ECU-A Electronic feedback carb w/TWC catalyst on Calif. only	EEC-II spark and EGR control + Model 2150 EEC-II controlled feedback carburetor. TWC catalyst.	EEC-II spark, EGR, feedback carburetors. TWC catalyst	EEC-III replaces feedback carb with electronic fuel metering (throttle body injection) TWC catalyst	EEC-III spark & fuel control on PROCO stratified charge engine on all by 1985
	IL-6 V-6			EEC-II			
	V-8		EEC-I inter-active spark and EGR control on Versailles. Model 2700 variable Venturi carb fuel meter-ing on Versailles and all 302 Calif.	EEC-II spark, EGR and feedback fuel control via the 2700 vv carb. TWC catalyst	Variable displacement V-8		

Source: Reference 19.

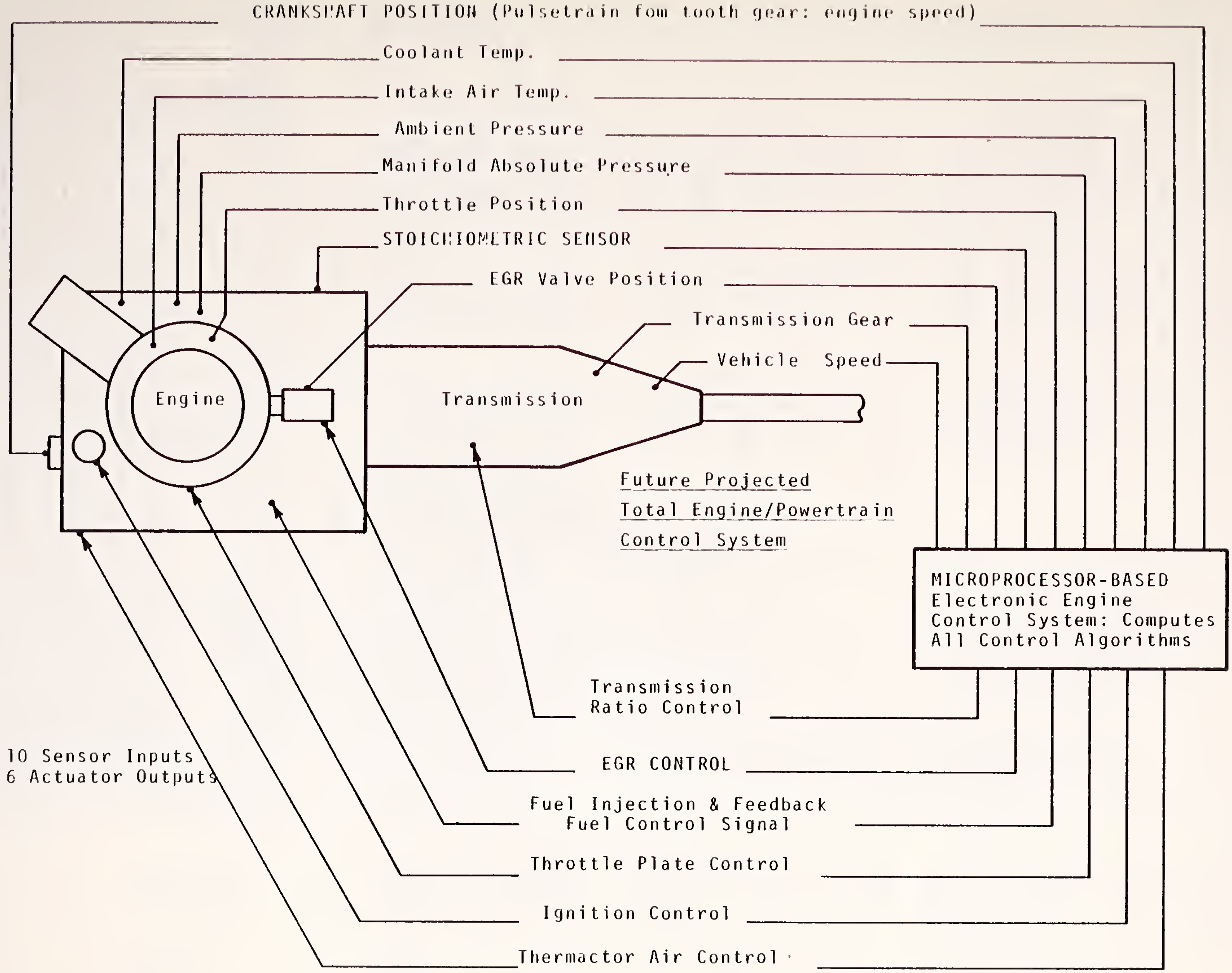


FIGURE 4-1. BASIC PARTS OF ENGINE CONTROL SYSTEM

for the 1980-1990 time frame. Table 4-2 outlines in detail the mechanical hardware, sensors and the software/microprocessor implementation strategy that will be required to produce the engine/powertrain control system for the 1980's. This is presented for each engine control variable individually allowing for the development of Table 4-3.

Table 4-3 presents various electronic powertrain control systems in order of increasing complexity, and provides preliminary estimates of fuel economy gain potentially achievable with key engine variables integrated into the engine/emission control system. The fuel economy gains presented for System A through F are not additive but instead represent fuel efficiency improvements on a system to system comparison. Systems G and H represent efficiency gains believed to be achievable with two transmission control concepts and do not include the effects of Systems A through F. Therefore, G or H is additive to any one of the systems A through F. Also note, that all estimates A through H are at the 1978 emission standards and that calibrating to the 1980 emission standards will cause a 12% reduction in fuel economy. It becomes obvious that System F (PROCO plus Spark Control) integrated with System H (continuously variable Transmission Control) will yield an estimated 34% fuel economy improvement at the 1978 standards of 1.5 HC/15.0 CO/2.0 NOx. When this system is calibrated to the 1981 standards of .4/3.4/1.0, the net fuel economy improvement is reduced to 22%. Note also, that Table 4-3 indicates that system C or D is required to achieve the 1980 standard with little or no loss in net fuel economy.

The significant findings with respect to electronic engine controls and their impact on improving the overall automotive fuel economy are:

1. As Table 4-1 indicates, the manufacturers believe in the central-general-purpose electronic controller for multi-variable, highly interactive and complex control requirements. As Chrysler and Ford have indicated, an electronic controller and a system of sensors, transducers, actuators and a significant portion of control software can be made

TABLE 4-2. ADVANCED TECHNOLOGY REQUIRED FOR ELECTRONIC CONTROL OF SIGNIFICANT POWERTRAIN VARIABLES (1980-1990 TIME FRAME)

POWERTRAIN CONTROL VARIABLE	Mechanization Hardware	Sensors	STRATEGY or Control Concept Implementation
SPARK Advance	Mechanical and Vacuum Advance mechanisms will be totally replaced by microprocessor-based Electronic Spark Control Systems including Electronic Ignition modules for improved spark quality and reliability.	Sensor requirements will include manifold absolute pressure or engine brake torque, engine speed, inlet air temperature, coolant temperature, Barometric pressure and Piston Position.	Initial Software program contains control strategy as defined by dynamometer data and off-line computer generated optimized engine calibration for fuel economy and emissions. Requires extremely flexible hardware.
EGR MASS FLOW	Single point entry sonic EGR valves will replace present systems. Multipoint entry variable-valve timing concept may be developed to improve EGR distribution to the engine cylinders.	Accurate control of EGR mass rate will require EGR pintle position, throttle position as well as sensor listed under spark advance.	Simple control of EGR versus manifold vacuum will be replaced by microprocessor based optimized software strategy developed as defined under spark advance.
FEEDFORWARD FUEL MASS FLOW Management	Carburetors (calibrated as volumetric flow devices) will be replaced by Electronic Fuel injection systems. Throttle-body injection, intake-port injection or direct cylinder-stratified charge injection systems will be used, purpose being improved cylinder distribution and reduced interactions with intake manifold.	Except for air mass flow meter-based EFI systems, all others are speed-density based requiring all sensors listed under spark advance and EGR in order to compute control law.	Speed-density control with EGR flow correction will be computed by microprocessor-based EFI control module. Initial system is calibrated to empirically derive engine volumetric efficiency expression.
FEEDBACK CONTROL Closed Loop: A/F Ratio, Spark Advance, EGR MASS FLOW	o Stoichiometric A/F set-point - used with TWC catalyst o Lean A/F setpoint - used with COC catalyst and Stratified Charge - PROCO TYPE engine systems o Knock Spark Control - used on all engines requiring NO_x abatement via EGR dilution.	o For Stoichiometric control a Zirconia dioxide sensor is required o For Lean A/F control a linearized Cobalt oxide or Titanium dioxide is used o For Knock Control an accelerometer is used o For closed-loop EGR valve control a EGR pintle position sensor is used.	Closed-loop EGR, SPARK and A/F Ratio control will correct for initial manufacturing variance and for system degradation with mileage accumulation. The closed-loop control laws and logic will be part of the software program stored in the microprocessor system, which is performing the open-loop strategy computations.
Lock-up Torque Converters and Continuously variable transmission ratios	Present Transmission designs will be replaced by o 4 forward speeds including overdrive with lock-up torque convertor o Continuously variable Transmission ratio design (CVT)	For both designs the control logic will require engine speed, vehicle speed, load, transmission gear and throttle position inputs	In both designs the control logic will be compoted by a micro-processor-based electronic module with the CVT control software being more sophisticated.
Dual Displacement Engines	Under low load conditions for V-8 or V-6 engines half the cylinders may be turned off via the Eaton valve deactivator/Solenoid System	Sensor requirements will be engine speed, vehicle speed, load, transmission gear and throttle position.	The ON/OFF logic may be computed by boolean logic digital circuits but a centralized computer may already have the sensory inputs required.
Thermactor Air Control	Requires presently available thermactor air pump, switching thermactor air valve and electrically actuated solenoids.	Sensor requirements include engine coolant, throttle position, catalyst temperature and inlet air temperature.	Microprocessor-based control strategy will switch thermactor air to atmosphere, upstream or mid-bed of a TWC/COC catalyst system.

Source: Reference 19.

TABLE 4-3. PRELIMINARY ESTIMATES OF FUEL ECONOMY IMPROVEMENTS AS DEFINED IN TABLE 4-1 AND TABLE 4-2.

SYSTEM	ELECTRONIC Engine Control Systems: Given in order of increasing complexity, all systems assume microprocessor-based electronic controls for maximum strategy flexibility, 1978 emission standards and Computer optimized calibration strategy for minimum fuel consumption.	AVERAGE FUEL ECONOMY GAIN PROJECTED OVER TOTAL U.S. AUTOMOTIVE Fleet. (Metro-HWY Value) (1978 BASELINE)
A	Improved Spark Advance Control (optimized Calibration) with COC catalyst and Thermactor Air Control.	5%
B	Improved EGR MASS FLOW CONTROL (optimized Calibration) includes closed-loop sonic valve control; plus integration of System A.	7%
C	Improved A/F Ratio Control via the Closed-Loop Concept (Simplest being applied to Carburetors first) with a TWC catalyst; plus Integration of Systems A, B.	10%
D	Improved A/F Ratio Open-loop Control via the Throttle-Body fuel injection (EFM) Concept; plus Integration of Systems A, B, C.	12%
E	Improved A/F Ratio Open-loop Control via the Intake-Port Fuel injection EFI) concept; plus Integration of Systems A, B, C.	15%
F	Improved A/F Ratio Open-loop Control via the Direct-Cylinder Stratified-Charge Fuel Injection (PROCO) Concept; plus Integration of Systems A and C (if closed-loop lean sensor exists).	20%
G	Computer Control of Lock-up Torque Converter Transmission.	12%
H	Computer Control of Continuously Variable Transmission Ratios	14%
I	Fuel Economy losses Due to Changing Emission constraints from 1978 ($1.5HC/15.0CO/2.0NO_x$) standards to the 1980 (.4/3.4/1.0) Standards.	-12%

general purpose with the calibration particular to a given vehicle/engine combination stored in a plug compatible ROM (READ ONLY MEMORY) CHIP.

2. As Figure 4-1 indicates, the implementation of a control system and strategy for the 1980-1990 time frame brings together all pertinent engine sensed and controlled variables in a highly interactive way. Table 4-3 indicates that from optimizing A/F ratio, spark, EGR and Transmission Control to meet the dynamic requirements of driver demand, engine/catalyst warm-up characteristics, vehicle driveability and 1980 emission constraints, a fuel economy improvement of 22% over a conventionally equipped car can be achieved. This microprocessor-based control system can implement highly non-linear, complex, interactive, time-variant control trajectories as defined by optimization of engine calibrations via off-line computer programs,[2,3,4] for the reduction and regression of engine dynamometer data. Also note, that since the central microprocessor contains all the sensory inputs required to compute the states of dual displacement and torque converter lock-up logic, it would be quite simple to incorporate these functions into software control.

3. The most important thing to consider is that the system optimized calibration outline above was developed on one engine at low mileage. Engine to engine variability and degradation with age greatly affect the performance and efficiency of the automotive fleet. Engine efficiency losses (10-15%) and exhaust emission increases (~30%) occur with open-loop control approaches due to engine degradation with time, environmental effects, manufacturing variances and fuel variations. In Reference 19 it was reported that fuel economy degraded by as much as 14% in 12,000 miles due to the loss of F/A ratio control. This is where electronic controls can be significant at maintaining fuel economy in the automotive fleet.

Electronic devices do not "wear" out and dominant failure modes do not relate to degradation over time, therefore reducing variability over time. Electronic controls, as Table 4-2 indicates, can accomplish interactive spark, EGR and fuel control in a "closed-loop" manner, allowing for compensation in one controlled variable, if another has indicated failure or slow-down. This, of course, also represents automatic compensation for high altitudes, barometric and temperature changes, fuel system wear, drift, and manufacturing electronic engine control can retrieve 90% of the 15% engine efficiency losses due to the above mentioned problems.

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